Urban Climate Research Center
Arizona State University

Cool Pavement Pilot Program

Joint Study between the City of Phoenix and Arizona State University

A report prepared for:
The City of Phoenix
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Streets PHX
STREET TRANSPORTATION DEPARTMENT

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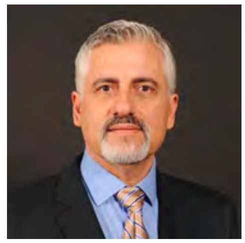

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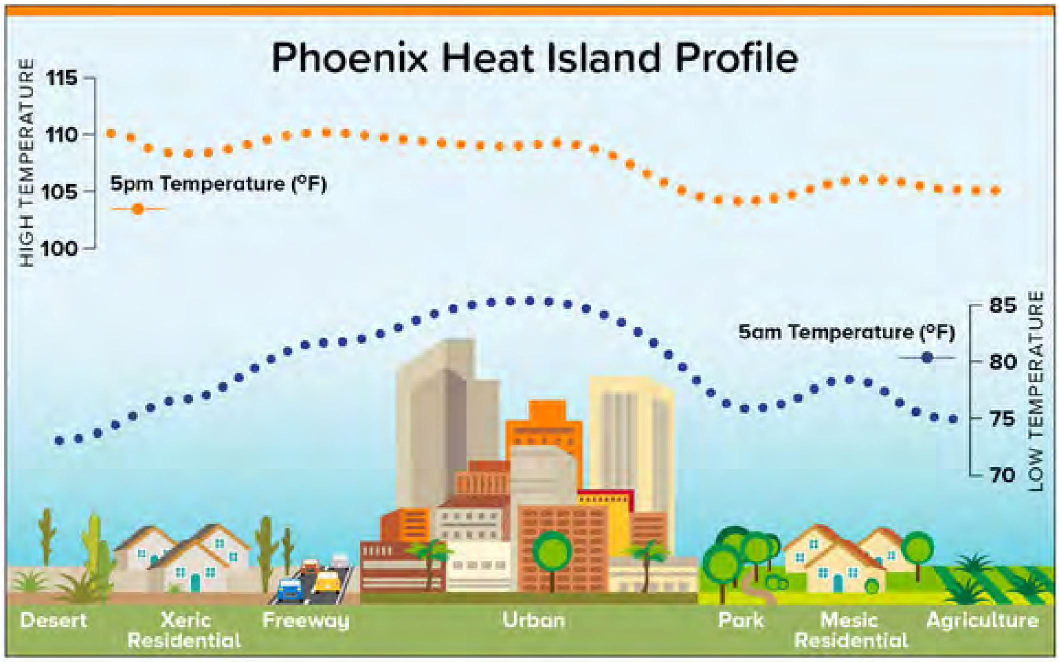
BACKGROUND

Many cities around the world, including the City of Phoenix, are experiencing elevated temperatures due to the built environment that are exacerbated by climate change. Paved surfaces with impervious materials, such as asphalt concrete (roads, sidewalks, parking lots, etc.), absorb and store heat during the day and release this heat overnight creating higher temperatures than surrounding rural areas. This phenomenon is known as the Urban Heat Island (UHI) effect (Figure 1). With paved surfaces comprising about 40% of the urban land area in Phoenix, they are often considered one of the primary causes of the UHI.

One of many strategies to mitigate increased temperatures and reduce heat storage in pavements is the use of coatings that reflect (rather than absorb) solar radiation to reduce the heat absorbed by the pavement, thus reducing surface temperatures. Lowering surface temperatures and the heat retained in the built urban environment may help reduce elevated day and nighttime air temperatures. Such reflective coatings are easy to apply to existing paved surfaces and, in most cases, use light-colored pigments and materials to increase reflectivity compared to traditional asphalt concrete roads.

The City of Phoenix recently initiated the Cool Pavement Pilot Program in which the City applied the product CoolSeal by GuardTop® to 36 miles of residential neighborhood roads and one public parking lot. This effort resulted in the most miles of road surface coverage with a reflective coating of any municipality globally. It is designed to achieve lower pavement surface temperatures through its lighter color and reflectivity. One neighborhood in each of the eight council districts of Phoenix was chosen for application of CoolSeal in consultation and with the support of the City Council Offices (Figure 2).



Urban heat profile of Phoenix showing air temperatures during daytime maximum (afternoon) and daytime minimum (overnight) based on weather station data in the region. This profile also demonstrates intraurban heat variability across the city, as affected by types of land cover (e.g., xeric landscape versus parks) and urban design.

Design by Lisa MacCollum / City of Phoenix.

THE PROJECT

July 15, 2020–July 14, 2021

The City of Phoenix Street Transportation Department partnered with the Rob and Melani Walton Sustainability Solutions Service at Arizona State University (ASU) and researchers from various ASU schools to evaluate the effectiveness, performance, and community perception of the new pavement coating. The data collection and analysis occurred across multiple neighborhoods and at varying times across days and/or months over the course of one year (July 15, 2020–July 14, 2021), allowing the team to study the impacts of the surface treatment under various weather conditions.

ON-SITE DATA COLLECTION

Numerous types of platforms and sensors were used to collect data, with further analysis completed in ASU laboratories.

In the field, a mobile human-biometeorological cart (MaRTy, short of Mean Radiant Temperature) and a vehicle completed traverses across three neighborhoods treated with CoolSeal and directly compared the measurements to untreated roads.

» **MaRTy** measures mean radiant temperature, air temperature, relative humidity, and wind speed and direction at pedestrian height at two-second intervals. MaRTy measurements were performed for 45–60 seconds at pre-defined stops.

MaRTy engages 12 radiometers that measure incoming radiation from six directions. This includes shortwave radiation (visible sunlight and UV radiation) and longwave radiation (heat emitted from hot surfaces). The shortwave and longwave radiation can be integrated into mean radiant temperature, the sum of all the radiation that hits a person's body from 360 degrees.

» **A vehicle** was equipped with fast-response, shielded, and naturally aspirated thermocouples to measure air temperature at 6 feet above the surface and an infrared radiometer attached to the bottom front of the vehicle (12 inches from the ground) to measure surface temperature of the pavement. These instruments collected readings at one-second intervals.

These mobile measurements were conducted for one hour at four times of day in each of the three neighborhoods: Before sunrise (~4:30–5:30am), solar noon (~12:00–1:00pm), afternoon at maximum daily air temperature (3:00–4:00pm), and after sunset (~7:30–8:30pm).

Long-term (7–10 months) assessments of performance indicators were also completed in the field:

» **iButton** sensors were buried within the pavement at 0.5 and 3in depth at 10 sites to determine sub-surface temperature across treated asphalt concrete roads.

» **A spectroradiometer** was used to measure changing solar reflectivity across treated asphalt concrete roads.

FINDINGS

The main research findings, outlined below are organized into three categories based on field campaign type and temperature metrics of importance. Together, these findings guide the holistic understanding of how the applied Cool Pavement (CP) treatment impacts the environmental temperatures and the people of the residential neighborhoods.

❶ Assessment 1

Detailed on-site, full-day assessments of local microclimates in three newly treated neighborhoods on extreme heat days, using both vehicle traverses and ASU's proprietary human-biometeorological mobile platform MaRTy, completed August & September 2020.

» **Surface temperatures** of the CP were systematically lower than non-treated asphalt concrete across all times of day. The CP surface temperature was, on average, 12.0°F and 10.5°F lower than the asphalt concrete at noon and afternoon hours (ranging from 9–16°F lower), and 2.4°F lower, on average, at sunrise. These lower surface temperatures indicate that the CP-treated roads are not absorbing as much heat as asphalt concrete roads, which helps to reduce overall levels of urban heat.

» **Air temperature** at 6 feet height was lower above the CP than the non-treated surface in the evening by approximately 0.5°F (ranging from 0.9°F lower to 0.1°F higher), which may help reduce the nighttime Urban Heat Island. Daytime differences averaged 0.3°F lower above the CP (ranging from 1.2°F lower to 0.2°F higher).

» **Mean radiant temperature**, representing a human's total radiant heat exposure walking on the surfaces, was increased at noon and afternoon hours by approximately 5.5°F, on average (ranging from 2.6 to 9.2°F higher), due to higher surface reflectivity. These higher values, which cause a reduction in human comfort, may be a necessary tradeoff to reduce surface temperatures using a reflective surface. These values were lower than the traditional asphalt concrete at sunrise and sunset (-0.5°F), and overall were similar to that experienced if walking over a concrete road.

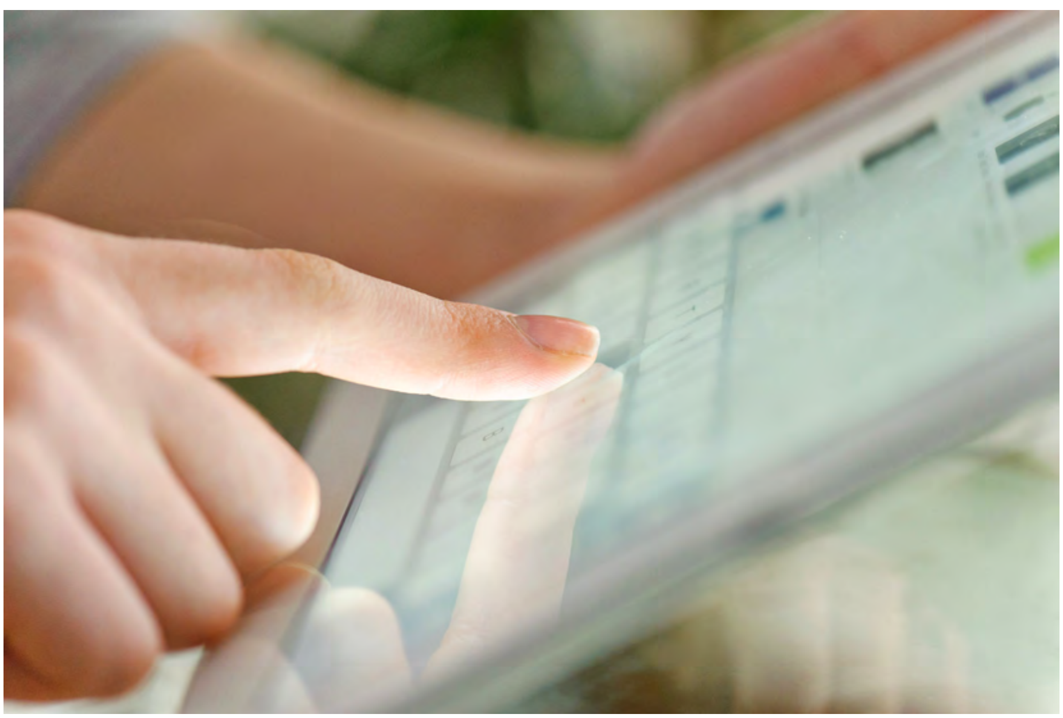
2 **Assessment 2**

Long-term (7–10 months) assessments of sub-surface temperature and solar reflectivity across treated asphalt concrete roads.

- **Sub-surface temperatures** beneath the CP were lower (4.8°F on average) than beneath the untreated asphalt concrete surfaces.
- **Surface solar reflectivity** of the CP was around 33–38% when installed and declined over time. The solar reflectivity 10 months after installation ranged from 19–30% across the eight neighborhoods. These reductions in reflectivity can result in less decreases in surface and sub-surface temperatures. For comparison, an untreated asphalt concrete surface had a consistent reflectivity of 12%, hence absorbing more solar radiation.

3 Resident interviews (early 2021) and surveys (June 2021) were conducted to understand the community perception and impact of the Cool Pavement. Survey results will continue to be tabulated through summer 2021. Preliminary findings include:

- **Satisfaction** with communication from the City about the CP pilot program and **interest** in learning more from the evaluation.
- **Divergent opinions** were expressed among residents concerning visual appeal and aesthetics, impacts on property values, the longevity of the coating, and surface friction.
- Collectively, the interview and preliminary survey results point to **opportunities** for additional resident engagement and education concerning CP.



RECOMMENDATIONS

Numerous important topline takeaways and recommendations arise from these initial Year 1 findings of the Cool Pavement Pilot Program. These include the following:

» The reductions in surface and sub-surface temperatures are positives for improving the lifespan and performance of the pavement. These factors are particularly important if the treatment is applied in the early years when the road is in very good condition. It is recommended that longer-term testing is completed to assess the changes in reflectivity, traction/skid, degradation, and subsurface temperature over time, particularly as the CP ages.

» While surface temperature reductions were strong, air temperature reductions were minor, yet influenced by numerous factors in an uncontrolled environment. It is recommended that enhanced fine-scale, precise assessments of air temperature changes are conducted, particularly to determine the energy, water, and health impacts of any temperature differences. Further work is also required to provide Phoenix-based guidelines to mitigate surface dirt, tire markings, and degradation due to a lack of precipitation and the hot climate.

» There was a wide range of resident opinions and perceptions that provided important insight into other CP considerations, which cannot be quantified using atmospheric sensors but are also important. Additional exploration of the potential use of this technology and other pavement coatings with similar performance yet a darker color may help improve public perception.

Additional and more detailed recommendations are provided as part of the full report based on study findings. A broad assessment of these physical and social indicators of the pavement coating at various timescales will provide critical insight and valuable information for the City of Phoenix to better understand how CP technology will impact street construction and maintenance operations, while also reducing the impact of asphalt concrete on urban heat levels in a hot desert climate.

2. Contents

3. Abbreviations

AC	Asphalt Concrete
ASU	Arizona State University
BBS	Bitumen Bond Strength
CP	Cool Pavement
PCC	Portland Cement Concrete
D1, D2, …	District 1, District 2, …
IRB	Institutional Review Board
NIR	Near Infrared Radiation
QS	Quarter Section
T_{air}	Air Temperature
TiO_2	Titanium Dioxide
T_{MRT}	Mean Radiant Temperature
T_{sfc}	Surface Temperature
T_{sub}	Sub-surface Temperature
UHI	Urban Heat Island
UVA	Ultraviolet A
UVB	Ultraviolet B

4. Background

Many cities around the world, including the City of Phoenix, are experiencing elevated temperatures due to the built environment that are exacerbated by climate change. This phenomenon is known as the Urban Heat Island (UHI) effect, in which urban areas experience localized warming compared to surrounding rural areas. The UHI is a complex phenomenon driven by many factors including canyon geometry, thermal properties of urban materials, anthropogenic heat, the urban greenhouse effect, effective reflectivity, reduction of natural evaporating surfaces, and reduced turbulent transfer of heat.[1–3] Paved surfaces with materials, such as asphalt concrete and Portland cement concrete (e.g., roads, sidewalks, parking lots), absorb and store heat during the day and release this heat in the evening and at night. These surfaces make up about 40% of the urban land area in Phoenix and are often considered one of the primary causes of the UHI.

One of many strategies to mitigate increased temperatures and reduce heat storage in pavements is the use of coatings that have moderate reflectivity,[4] which have been shown to have less negative effects at street level (e.g., visibility) than highly reflective coatings.[5] These coatings, by design, reflect solar radiation to reduce the heat absorbed by the pavement, thus reducing surface temperatures. They are easy to apply to existing paved surfaces and, in most cases, use light-colored pigments and materials (such as nano-particles) to increase reflectivity. Some of the potential advantages of using reflective coatings include reduced heat absorption, conduction, and significantly reduced surface temperatures, thus helping to mitigate the UHI, especially during the evening hours and after sunset when the UHI is often strongest. Other benefits may include reduced near-surface air temperatures, especially during the day. The City of Phoenix recently initiated the Cool Pavement Pilot Program in which the City applied the product CoolSeal by GuardTop® to 36 miles of residential neighborhood roads and one public parking lot. According to the company's safety data sheet, CoolSeal is composed of 10–25% asphalt, 4–10% aggregate blend, 0–10% poly-glass polymer liquid, 0–10% vinyl-acrylic copolymer, 25-45% titanium dioxide, and up to 55% water. It is designed to achieve lower pavement surface temperatures through its lighter color and reflectivity. One neighborhood in each of the eight council districts of Phoenix was chosen for application of CoolSeal in consultation and with the support of the City Council Offices (**Figure 2**).

In partnership with scientists from Arizona State University (ASU), the City of Phoenix evaluated the performance of the reflective Cool Pavement (CP) sealcoat based on various metrics measured on the treated pavement compared to the untreated areas with traditional asphalt concrete in the same residential neighborhoods. The research was designed to understand the effectiveness of CP across the neighborhoods, times of day, and across months since being installed in late summer 2020, as well as the community perceptions of the CP surface coating.

City of Phoenix: Cool Pavement Application Neighborhoods

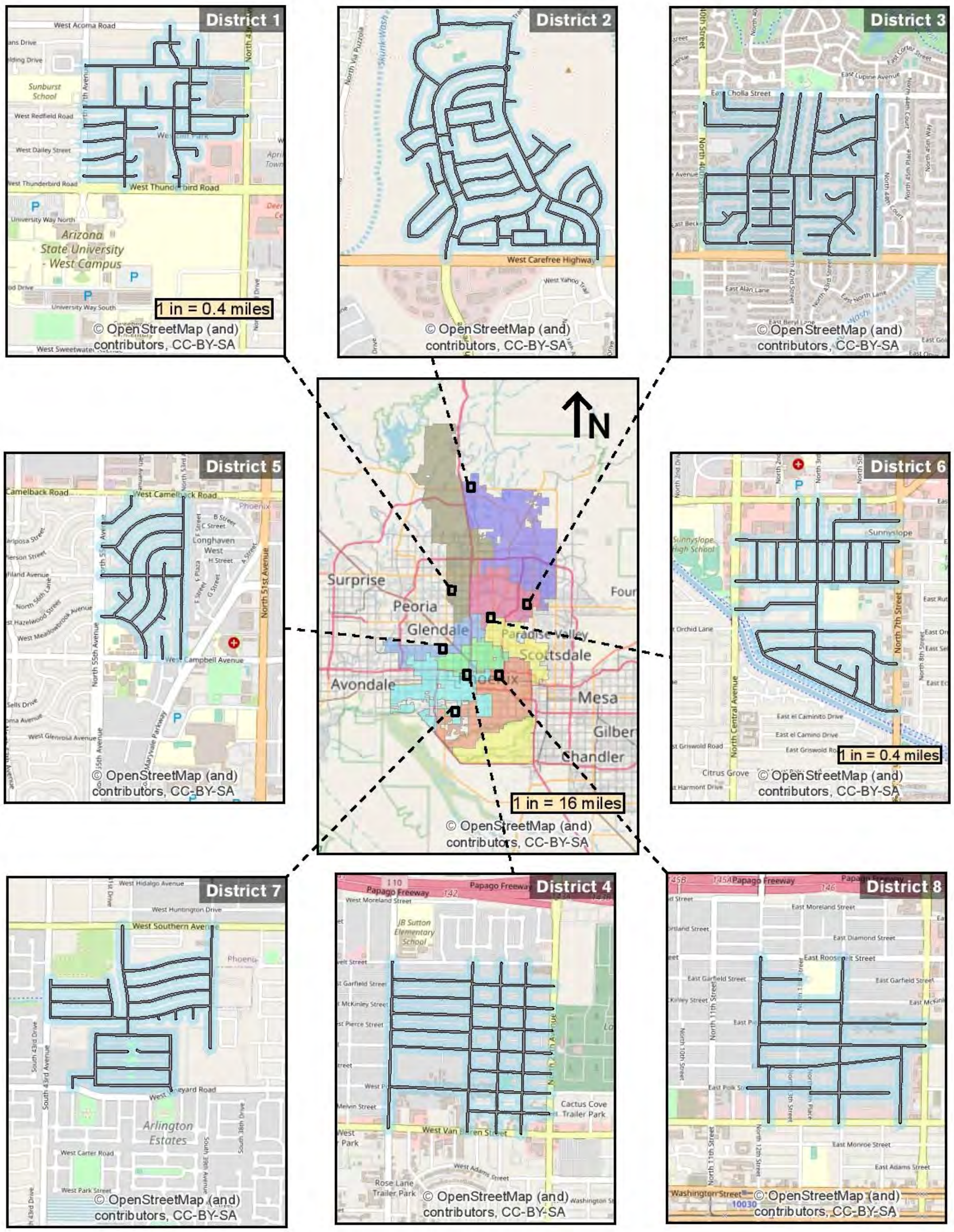


Figure 2: Center: City of Phoenix with its council districts (colored) and the location of the Cool Pavement-treated neighborhoods. Outside: Cool Pavement-treated roads in each of the 8 districts.

5. Study Design and Implementation

In this study, fieldwork was performed to collect quantitative data to assess the impact of CP on four temperature/heat metrics (air temperature, surface temperature, subsurface temperature, and mean radiant temperature) and its long-term solar reflectivity. These biophysical variables are described in **Table 1**.

Table 1: Descriptions of the biophysical environmental data collected in the current study and purpose of each. The five parameters help in the holistic understanding of how the Cool Pavement impacts the environment of the residential neighborhoods.

Quantitative Metric	Definition and Importance
Air temperature (T_{air})	A measure of how hot or cold the air is. T_{air} drives building energy use for cooling/heating of buildings and is a key metric to define the UHI magnitude (difference between T_{air} in a city compared to T_{air} in the rural surroundings).
Surface temperature (T_{sfc})	Quantifies the "touch" temperature of a surface, such as roads, buildings, and roofs. In this project, the surfaces measured included sidewalks and the treated and untreated asphalt concreate roads. T_{sfc} is important in areas where people or animals directly touch a hot surface without the protection of clothing. T_{sfc} is positively correlated with higher emission of infrared radiation (longwave) from a surface. It also impacts T_{air} above the surface (for example, if $T_{sfc} > T_{air}$, the air above the surface gets warmer).
Sub-surface temperature (T_{sub})	A measure of pavement temperature below the surface. Additional heat at the surface can be transferred (or conducted) to layers beneath the surface, which can soften the asphalt concrete and affect pavement performance and durability. This would typically require stiffer or modified asphalt binders to better resist the elevated temperatures.
Mean radiant temperature (T_{MRT})	The total heat load on the human body due to the exposure to shortwave and longwave radiation from all directions (sky plus all horizontal and vertical surfaces) at a given time and location. This exposure includes the longwave radiation emitted from hot surfaces, such as an asphalt parking lot in the summer, and the shortwave radiation from the sun and reflected from surfaces in unshaded places.
Surface reflectivity	The effectiveness of a surface in reflecting radiant energy. Here, it is the fraction (or %) of the incoming solar radiation that is reflected from the pavement throughout the day. More reflective surfaces have higher percent reflectivity (such as snow). A higher surface reflectivity means that less energy is stored in the surface (producing lower T_{sfc}) and instead is reflected into the atmosphere.

This study's fieldwork included 1) detailed, high-resolution measurements of T_{air}, T_{sfc}, and T_{MRT} across three full days in three neighborhoods using two mobile platforms, 2) long-term (7-month) spectroradiometer readings of reflectivity in eight neighborhoods, 3) and long-term (10-month) sub-surface temperature assessments in various locations. Methods in **Section 5.2** outline how each of these metrics were measured. In addition, resident interviews and surveys were conducted to understand the community perception and impact of CP.

5.1. Main Research Questions

- What are the differences in T_{sfc}, T_{air}, and T_{MRT} for traditional asphalt concrete surfaces versus CP across the day in the same neighborhoods on hot days?
- What are the temperature differences in top and bottom layers of the asphalt concrete beneath an untreated and CP-treated surface?
- How does the solar reflectance of CP degrade with time?
- What are the perceptions of city residents regarding the benefits and potential drawbacks of the CP?

5.2. On-Site Data Monitoring and Analysis

5.2.1. MaRTy and Vehicle Traverse Measurements

Three one-day fieldwork campaigns were performed in CP-treated neighborhoods in Districts 1, 5, and 8 during August and September 2020 under hot and sunny conditions (**Table 2**). Two sensing platforms were used to measure the impact of CP on T_{sfc}, T_{air}, and T_{MRT} (**Figure 3**):

- MaRTy (**Figure 3a**) is a biometeorological cart that measures T_{MRT}, T_{air}, relative humidity, and wind speed and direction at pedestrian height at 2-second intervals.
- Fast-response, shielded, and naturally aspirated thermocouples (**Figure 3b**) were attached to a vehicle to measure T_{air} at 2 meters above the surface (~6 ft); an infrared (IR) radiometer (**Figure 3c**) was attached to the bottom front of the vehicle ~1 ft from the ground to measure T_{sfc} of the pavement. The thermocouples and IR sensor measured at 1-s intervals.

Table 2: Districts and dates of measurements using the MaRTy platforms and vehicle traverses. All measurements were taken within the following time windows: pre-sunrise, 12–1pm, 3–4pm, post-sunset. The minimum, mean, and maximum daily air temperature (T_{air}) are from the National Weather Service weather station at Phoenix Sky Harbor to represent conditions for the area.

Date	District	Minimum Daily T_{air}	Mean Daily T_{air}	Maximum Daily T_{air}
Aug 18, 2020	D8 (Garfield)	89.9°F	102.7°F	114.9°F
Sept 5, 2020	D5 (Maryvale)	84.0°F	99.7°F	114.0°F
Sept 20, 2020	D1 (Westcliff)	78.0°F	92.7°F	105.9°F

All sensors were research-grade and calibrated. On each fieldwork day, mobile measurements were conducted for one hour at four times of day: Before sunrise (generally between 4:30–5:30am), solar noon (between 12:00–1:00pm), afternoon at maximum daily air temperature (between 3pm and 4 pm), and after sunset (generally between 7:30–8:30pm). Mobile measurements using a vehicle traversed the CP-treated residential neighborhood and an adjacent reference neighborhood with asphalt concrete (the Garfield neighborhood in D8 also contained two 0.25 miles of road with a concrete road surface for T_{sfc} and T_{MRT} comparisons). MaRTy measurements were performed for 45–60 seconds at pre-defined stops; car traverses looped through the neighborhoods twice over a pre-determined route at an approximate speed of 15 to 20 mph where each loop took ~30 minutes. This car speed was chosen to ensure that a representative number of temperature samples were taken in each area while staying near traffic speeds and allowing wind flow over the sensors.

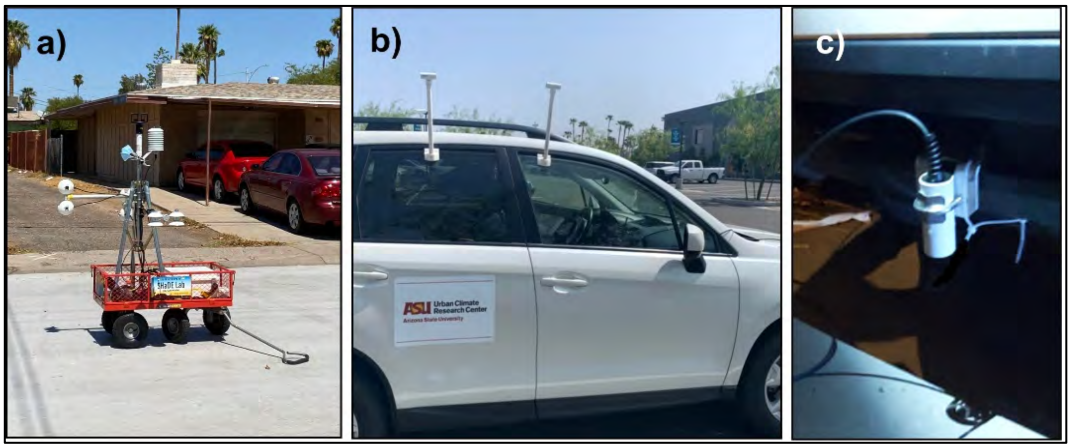


Figure 3: Instruments used for traverse measurements: **a)** human-biometeorological sensor platform, MaRTy, collects data over Cool Pavement; b) air temperature sensors (thermocouples) attached to a car; **c)** surface temperature sensor attached to a car facing the pavement.

Figure 4: Surface reflectivity measurements of Cool Pavement with a spectroradiometer.

5.2.2. Spectroradiometer Reflectivity Measurements

Monthly recurring solar reflectivity measurements were performed in all CP-treated residential neighborhoods between November 2020 and May 2021. An untreated asphalt concrete road in District 3 served as reference control. Surface solar reflectivity of CP and the reference asphalt was measured with an ASD FieldSpec 4 Wide-Res Field Spectroradiometer (**Figure 4**). Up to ten data points per location were collected on the north side of the road next to the concrete sidewalk to minimize the impact of traffic on road conditions.

5.3. Thermal IR Helicopter Overflights

Helicopter overflights with a hand-held, high-resolution infrared camera were performed before/at sunrise and during the noon hour on August 7, September 10, and October 21, 2020. Overflights covered extensive areas of CP and nearby asphalt concrete surfaces of varying ages. August 7 photos (**Figure 5**) show T_{sfc} before the neighborhoods were treated with CP. September 10 was the midpoint of all CP treatments showing four neighborhoods with CP and four neighborhoods without. On October 21, all CP application had been completed. The goal of this task was to provide a qualitative evaluation and comparison of paved surface temperatures across the neighborhoods for use by researchers and by the City. The images provide visual data regarding average T_{sfc} over segments of paving across various times of day and season.

Figure 5: Conventional paving in Phoenix, taken on August 7, 2020 prior to any Cool Pavement installation. Top: District 4; Bottom: District 5. Images taken around 12–1pm, showing temperature comparisons between conventional asphalt concrete roadways, roofs, open lots, and lawns/trees.

5.4. Community Survey: Perceptions of Cool Pavement

The research team conducted online surveys of residents (in English and Spanish) in CP-treated neighborhoods to understand their perceptions of and experiences with the CP coating. The survey was developed based on resident feedback the research team received while conducting neighborhood transects, guidance from City staff, and comments from four exploratory interviews with residents conducted in November and December 2020. The survey included approximately 30 questions, most of which were closed-ended. Major themes addressed in the survey include communication from the City, overall satisfaction with the CP, specific potential impacts of the CP, and interest in future engagement with CP research. Basic demographic information and data about day-to-day neighborhood activities were also collected. A small pilot test of the online survey was conducted ahead of the 2021 warm season and received 10 responses.

Feedback from the interviews and survey pilot test led to an adjusted timing for the full survey to June 2021 as some residents felt unable to evaluate the potential cooling effects of the CP until the hot weather arrived. The full survey was launched in mid-June 2021 with a target sample size of at least 354 residents. Sampling is based on random selection of addresses within each of the eight CP-treated neighborhoods. Postcards with a QR code and hyperlink (**Figure 6**) were mailed to 2,000 randomly selected addresses (~250 per neighborhood) with an estimated response rate of 20%. The survey was also available online in English and Spanish (see **Appendix 1** for a full version of the survey in English). Each survey respondent was compensated with a $5 gift card. ASU Institutional Review Board (IRB) approval was obtained in 2020 to perform the surveys and interviews.

Figure 6: Cool pavement survey postcard sent to residents in Cool Pavement-treated neighborhoods.

5.5. Subsurface Temperature Performance

iButton temperature sensors were installed in the asphalt concrete layer of the eight district neighborhood roads, the Maricopa County parking lot at Madison St., and at Esteban Park. The sensors were placed in the asphalt concrete layer of roads that received CP and at adjacent locations with conventional asphalt concrete surfaces. A total of 20 sensors (10 control and 10 CP) were deployed (**Figure 7**).

Figure 7: Temperature sensors (iButtons) are placed at ½ inch and 3 inches depth in the asphalt to measure subsurface temperatures.

The sensors were installed at a depth of ½ inch and 3 inches from the surface to monitor T_{sub} changes for the duration of the project. Sensors recorded T_{sub} every 20 minutes, and measurements were downloaded approximately every two months. In addition, video logs were recorded for some of the sites prior to the CP application to visually assess pavement conditions. A visual pavement condition survey was also conducted in June 2021 to assess the surface condition of CP after 10 months of its application (**Appendix 2**). In the laboratory, preliminary tests were conducted on the CP product to determine its thermal conductivity (based on a novel method developed at ASU), heat capacity, and bonding strength. Finally, preliminary life cycle cost and a pavement performance analysis based on the thermal properties and field temperatures were completed.

6. Study Results and Discussion

6.1. Air Temperature

The on-site, vehicle-based T_{air} measurements over CP and untreated asphalt concrete are shown in **Table 3**. The highest mean T_{air} values in each neighborhood were found in the afternoon, with 113.8°F in Garfield over asphalt concrete, 111.5°F in Maryvale over CP, and 102.5°F in Westcliff over asphalt concrete. Minimum T_{air} for all neighborhoods occurred before sunrise with little variation in T_{air} across the neighborhoods within the data collection time windows.

The T_{air} difference between CP and asphalt concrete (i.e., $T_{air}^{CP} - T_{air}^{asphalt}$) was strongest, on average, just after sunset, at -0.5°F (ranging from -0.9°F to +0.1°F; **Table 4**), which is important in reducing the nighttime UHI. Across all neighborhoods and loops, the cooling effect of CP reached -1.2°F in Maryvale in the afternoon (loop 1). Daytime differences averaged 0.3°F lower above the CP, for which warming was found before sunrise in D5, Maryvale, and D1, Westcliff (0.3°F higher).

In summary, the T_{air} was cooler over CP or equivalent to that over asphalt concrete after sunset in all neighborhoods. A lowered yet varied T_{air} over CP compared to asphalt concrete was predominantly found during the measurements in all neighborhoods and at all times except before sunrise.

Table 3: Mean air temperature ($T_{air,}$ °F) at 2-meter (~6 feet) height by neighborhood, time of day, and loop. SD: Standard deviation. Before sunrise (~4:30–5:30am), noon (12–1pm), afternoon (3–4pm), after sunset (~7:30–8:30pm).

Neighborhood	Mean T_{air} ± SD (°F) Before sunrise		Mean T_{air} ± SD (°F) Noon		Mean T_{air} ± SD (°F) Afternoon		Mean T_{air} ± SD (°F) After Sunset	
D8 Garfield	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**
Asphalt	93.2 ± 0.3	92.6 ± 0.2	109.5 ± 0.7	109.9 ± 0.8	113.8 ± 0.7	113.0 ± 0.7	106.3 ± 0.6	105.0 ± 0.7
Cool Pavement	93.2 ± 0.4	92.7 ± 0.4	109.1 ± 0.8	109.9 ± 0.8	113.7 ± 0.7	113.3 ± 0.6	105.6 ± 0.5	104.9 ± 0.6
D5 Maryvale	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**
Asphalt	90.2 ± 0.7	90.7 ± 0.5	109.5 ± 1.4	109.5 ± 1.4	111.2 ± 1.4	111.3 ± 1.3	103.0 ± 1.1	101.4 ± 1.2
Cool Pavement	90.5 ± 0.5	90.8 ± 0.4	109.0 ± 1.2	109.2 ± 1.1	110.0 ± 1.0	111.5 ± 1.6	102.7 ± 0.9	101.5 ± 0.9
D1 Westcliff	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**
Asphalt	76.9 ± 0.5	77.1 ± 0.5	100.0 ± 1.4	100.3 ± 1.4	102.5 ± 0.8	102.3 ± 0.7	92.2 ± 2.0	90.3 ± 1.6
Cool Pavement	77.2 ± 0.5	77.3 ± 0.5	99.4 ± 1.3	99.8 ± 1.4	102.4 ± 0.7	102.2 ± 0.6	91.4 ± 1.1	89.5 ± 0.9

Reasons for small T_{air} differences within the CP versus asphalt concrete areas of the neighborhoods are many. First, the T_{air} impact is distributed over a large area due to convective winds between areas of CP, asphalt concrete, and over residential yards with diverse land covers (from vegetated lots to fully xeriscaped yards to dirt lots). Second, shading and irrigation variability affects mixing of air and thus T_{air} distribution. Third, the neighborhoods are relatively small, and hence the area of CP application is small, which reduces the effect on T_{air}. For example, some roads in the Garfield neighborhood were still untreated asphalt concrete at the time of measurement, which could reduce the potential cooling effect of the implementation. Finally, the T_{air} sensors placed 2 meters (~6ft) above the surface may pick up less differences because air mixes more the further up you move from the ground surface. Suggestions for future work to assess vertical temperature gradients and other localized effects on T_{air} are provided in Section 7.

Table 4: Mean air temperature (T_{air}, °F) differences at 2-meter (6 feet) height between Cool Pavement (CP) and asphalt concrete (asphalt) areas by neighborhood, time of day, and loop (T_{air}^{CP}–$T_{air}^{asphalt}$). Positive values indicate that CP areas were warmer than asphalt concrete, and negative indicate CP areas were cooler than asphalt concrete. Before sunrise (~4:30–5:30am), noon (12–1pm), afternoon (3–4pm), after sunset (~7:30–8:30pm).

Neighborhood	Mean T_{air} (°F) Before Sunrise		Mean T_{air} (°F) Noon		Mean T_{air} (°F) Afternoon		Mean T_{air} (°F) After Sunset	
D8 Garfield	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**
$T_{air}^{CP} - T_{air}^{asphalt}$	-0.0	0.1	-0.4	0.0	-0.2	0.3	-0.6	-0.1
D5 Maryvale	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**
$T_{air}^{CP} - T_{air}^{asphalt}$	0.3	0.1	-0.5	-0.3	-1.2	0.2	-0.4	0.1
D1 Westcliff	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**
$T_{air}^{CP} - T_{air}^{asphalt}$	0.3	0.1	-0.6	-0.5	-0.2	-0.2	-0.9	-0.8

6.2. Surface Temperature

6.2.1. Helicopter Overflights

Helicopter overflights with an IR camera before (**Figure 5**), during, and shortly after the applications of CP in various neighborhoods allow direct comparison of T_{sfc} of the CP compared with aged untreated asphalt concrete in nearby locations. **Figure 8** shows side-by-side digital camera and infrared images from these helicopter flights. In each case, the image post-processing uses actual atmospheric temperature and humidity and an estimated surface emissivity of 0.95 to quantify T_{sfc}. Due to flight constraints on particularly hot days, all images are from days with partly cloudy skies and moderately hot air temperatures (~90°F in mid-afternoon). In each case, in the mid-afternoon hours the CP surface is 10–11°F cooler than the untreated asphalt concrete.

Figure 8: Side-by-side digital camera and infrared images of several locations where Cool Pavement was applied from Sept 10, 2020, 12:45pm (top), Sept 10, 2020, 1:08pm (middle), and Oct 21, 2020, 1:12pm (bottom).

6.2.2. On-site Surface Temperature

The on-site, vehicle-based T_{sfc} measurements over CP, concrete (for Garfield), and asphalt concrete are shown in **Table 5**. The highest mean T_{sfc} values of ~150.4°F were found on the asphalt concrete in the Garfield neighborhood from 3–4pm, the hottest time of the day. On this day and time, the CP also reached high T_{sfc} (~144.7°F), equivalent to that found on concrete. Minimum T_{sfc} values occurred just before sunrise, with Westcliff—sampled the latest in the year and thus with shorter days and less intense sunlight—showing the lowest average minimum T_{sfc} (~83.0°F for asphalt concrete, 3°F higher than the CP T_{sfc} minimum for Maryvale).

The T_{sfc} values of the CP were, on average, considerably lower than asphalt concrete during daytime measurements (**Table 6**). A maximum average difference between asphalt concrete and CP of 16.0°F was found in the Westcliff neighborhood at noontime for loop 1 (and 15.6°F for loop 2), with similarly large differences found from 3–4pm in the same neighborhood (13.7 and 12.4°F for loops 1 and 2, respectively). The lower T_{sfc} of the CP was also evident during the noon and afternoon periods for the Maryvale and Garfield neighborhoods, reaching maximum differences of 10.8°F and 10.0°F for the respective times in Maryvale. The T_{sfc} differences were least at sunrise, where the asphalt concrete and CP were nearly equivalent (differences ranged from 1.6 to 3.0°F at this time). The T_{sfc} difference between asphalt concrete and CP is illustrated in **Figure 9** for the Maryvale noon measurements. An on-the-ground image of surface temperature differences between CP and asphalt concrete is provided in **Figure 10**, with CP on the left.

Table 5: Mean surface temperature (T_{sfc}, °F) values of asphalt concrete (asphalt), concrete (for D8 Garfield), and Cool Pavement (CP) by neighborhood, time of day, and loop. SD: Standard deviation. Before sunrise (~4:30–5:30am), noon (12–1pm), afternoon (3–4pm), after sunset (~7:30–8:30pm). Note: each loop of the vehicle traverse took ~30min of the time window.

Neighbor-hood	Mean T_{sfc} ± SD (°F) Before Sunrise		Mean T_{sfc} ± SD (°F) Noon		Mean T_{sfc} ± SD (°F) Afternoon		Mean T_{sfc} (°F) After Sunset	
Garfield D8	**Loop 1**	**Loop 2**	**Using MaRTy data***		**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**
Asphalt	98.1 ± 1.1	97.6 ± 1.1	144.8 ± 1.1		152.0 ± 4.1	149.6 ± 4.3	116.1 ± 1.8	115.2 ± 1.5
Concrete	96.6 ± 1.1	96.0 ± 1.5	135.8 ± 0.4		145.4 ± 2.1	143.9 ± 1.8	115.9 ± 1.3	114.1 ± 1.4
CP	95.5 ± 0.9	95.1 ± 0.9	135.0 ± 1.2		143.0 ± 2.5	141.2 ± 2.6	111.2 ± 1.4	110.5 ± 1.3
D5 Maryvale	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**
Asphalt	93.3 ± 1.1	93.0 ± 1.2	145.6 ± 4.8	147.4 ± 5.1	145.0 ± 5.8	142.9 ± 5.3	110.2 ± 1.8	109.2 ± 1.8
CP	91.6 ± 1.1	91.4 ± 1.1	135.3 ± 3.0	136.5 ± 2.4	135.6 ± 3.1	133.0 ± 3.4	106.4 ± 1.6	105.3 ± 1.5
D1 Westcliff	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**
Asphalt	83.3 ± 1.5	83.0 ± 1.3	139.0 ± 5.1	141.7 ± 4.3	137.1 ± 5.0	133.1 ± 5.0	102.1 ± 2.4	100.3 ± 2.4
CP	80.3 ± 1.1	80.3 ± 0.9	122.9 ± 3.9	126.0 ± 3.7	123.4 ± 2.9	120.7 ± 2.5	96.3 ± 1.5	95.0 ± 1.4

**Infrared temperature monitor on vehicle had data collection error, hence T_{sfc} from the MaRTy biometeorological cart were used, and therefore only one loop was measured over the hour.*

Table 6: Mean surface temperature difference (ΔT_{sfc}, °F) between Cool Pavement (CP) and asphalt concrete (asphalt) or concrete (for D8 Garfield) and asphalt concrete (asphalt) by neighborhood, time of day, and loop. A negative value indicates the CP or concrete having lower T_{sfc} than asphalt concrete (asphalt).

Neighborhood	ΔT_{sfc} (°F) Before Sunrise		T_{sfc} (°F) Noon		T_{sfc} (°F) Afternoon		T_{sfc} (°F) After Sunset	
D8 Garfield	**Loop 1**	**Loop 2**	**Using MaRTy* data**		**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**
$T_{sfc}^{concrete} - T_{sfc}^{asphalt}$	-1.6	-1.7	-9.0		-6.6	-5.7	-0.2	-1.1
$T_{sfc}^{CP} - T_{sfc}^{asphalt}$	-2.7	-2.6	-9.8		-9.0	-8.3	-4.9	-4.7
D5 Maryvale	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**
$T_{sfc}^{CP} - T_{sfc}^{asphalt}$	-1.7	-1.6	-10.3	-10.8	-9.4	-10.0	-3.8	-3.9
D1 Westcliff	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**	**Loop 1**	**Loop 2**
$T_{sfc}^{CP} - T_{sfc}^{asphalt}$	-3.0	-2.7	-16.0	-15.6	-13.7	-12.4	-5.7	-5.4

**Infrared temperature monitor on vehicle had data collection error, hence T_{sfc} from the MaRTy biometeorological cart were used.*

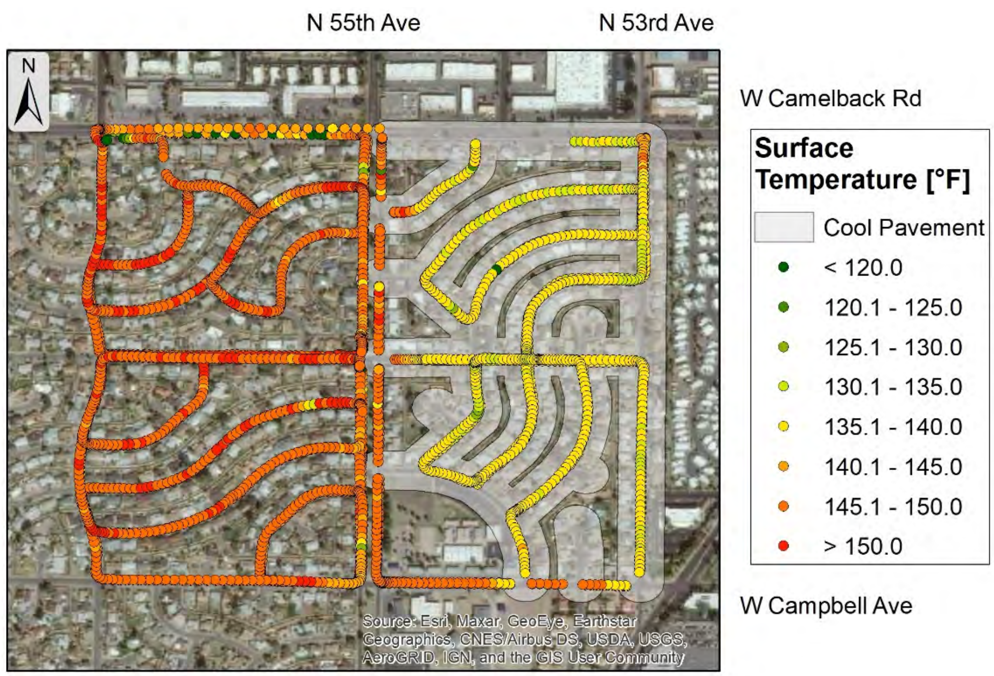


Figure 9: Map of measured and time-detrended surface temperature of both loops for 12:30 PM on September 5, 2020, in the Maryvale neighborhood in district 5. Note that all other similar surface temperature maps by location and time of day are in Appendix 3.

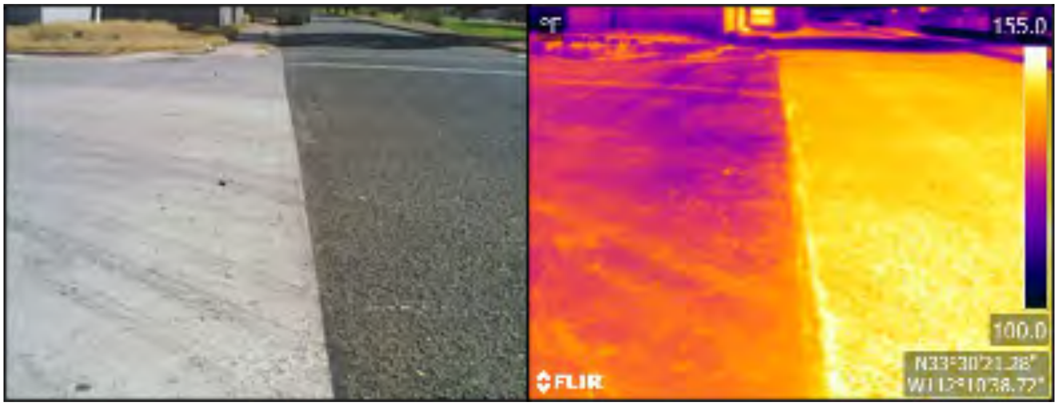
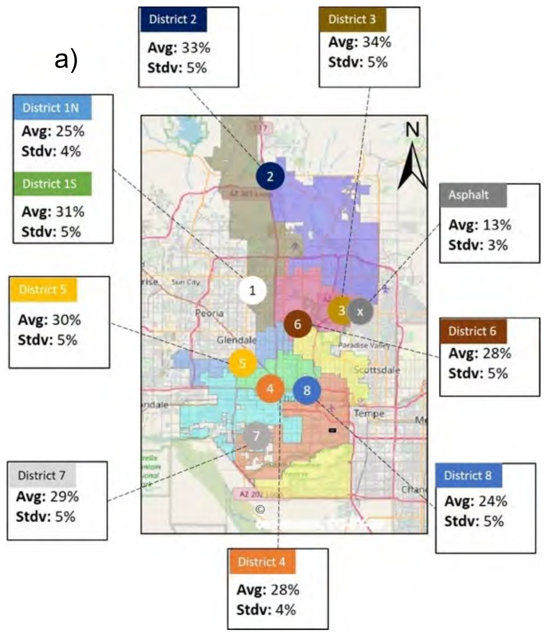


Figure 10: Side-by-side visible and infrared images of a junction between Cool Pavement (left) and untreated asphalt concrete (right), taken Sept. 9, 2020 at 1:30pm.

6.3. Surface Reflectivity

Reflectivity measurements, taken over 7 months, are shown by district in **Figure 11a**. Measurements started when CP was 1–3 months old, depending on the neighborhood. On average across the 7 months, D3, D2, and D1S were the most reflective (average reflectivity of 34%, 33%, and 31% of the incident shortwave radiation, respectively), while D8, D1N, and D4 were the least reflective (average reflectivity of 24%, 25%, and 28% of the incident shortwave radiation, respectively). These reflectivity values are much higher than the average asphalt concrete reflectivity of ~12–13% in the control segment. From November 2020 to May 2021, all districts saw decreases in the reflectivity (**Figure 11b; Figure 12**), with an all-district average change from 34% to 25% for NIR (700–2500nm) and 26–18% for visible (400–700nm). These decreases varied considerably by district, where D1S, D2, D5, and D6 all lowered by 10–12% in 7 months, yet D4, D7, and D8 had reflectivity decreases of 5–6%. These differ from the general averages provided above because the initial reflectivity measured in November varied from 24–38%; reflectivity values taken right after CP application in August, September, or October would most likely have been similar across the districts.

Rainfall and street sweeping around Dec. 20–25, 2020 increased the reflectivity in three districts (D2, D3, D7), supporting the increase in overall reflectivity in **Figure 11**, yet the remaining districts were unaffected. Rainfall on March 25, 2021 resulted in an increase in reflectivity in D4. The lowest average reflectivity, based on **Figure 11a**, seemed to occur in neighborhoods with either higher traffic volume and/or generally more dust/dirt that covers the streets over time. Locations D1N and D1S differ by around 6% even though they are on the same street within a distance of 15 feet. This is likely due to the design of the street where the northern side (D1N) is trafficked much more than the southern side (D1S) of the street, which would lead to more rubber residual and wear on the surface than without or with little traffic.



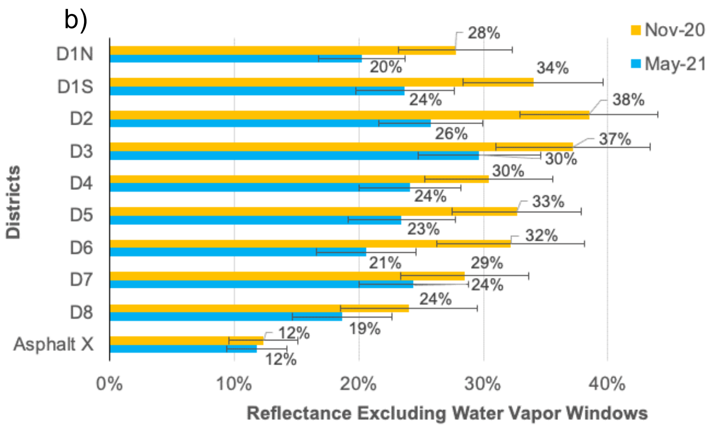


Figure 11: a) Average surface reflectivity of CP in each district for Nov 2020–Mar 2021.
b) Reflectivity in Nov 2020 compared to Mar 2021 across all wavelengths, excluding water vapor windows.

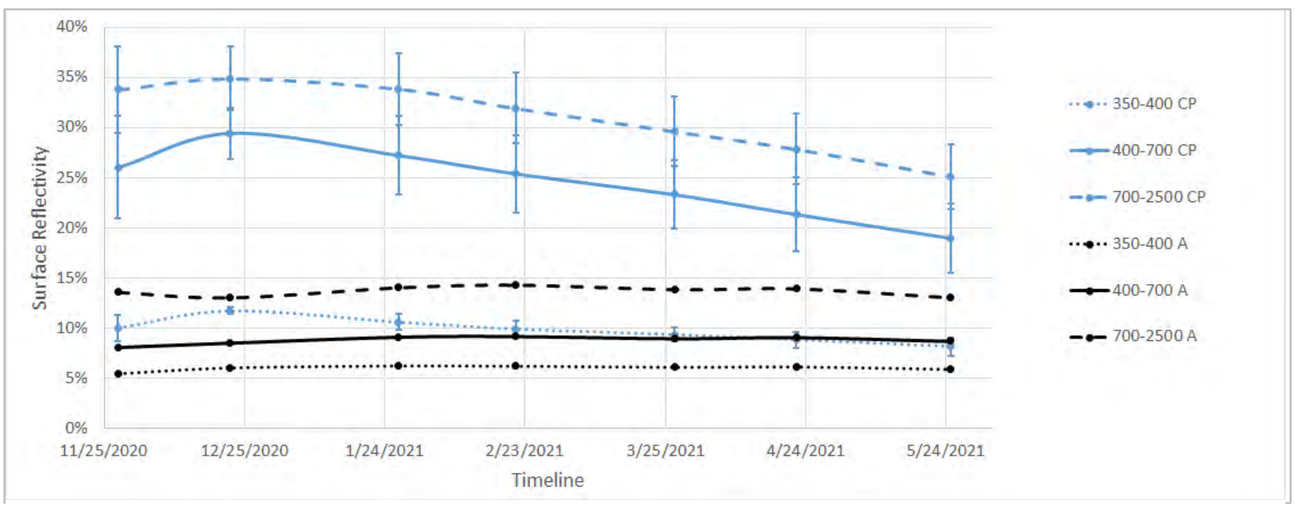


Figure 12: Solar reflectivity over time for Cool Pavement (CP) and asphalt concrete (A) across three wavelength ranges: ultraviolet A (UVA) (350–400nm), visible (400–700nm), and near infrared (near infrared (NIR), 700–2500nm). CP data represents averages for all 8 districts.

Note that the ultraviolet B (UVB) reflectance of various urban surfaces, including fresh CP, aged CP, and asphalt concrete, were tested at the end of June 2021, with results forthcoming. UVB is the portion of the UV spectrum that causes sunburns and skin cancer. Because of the use of titanium dioxide (TiO_2) bound in the CP made by GuardTop®, which absorbs UV radiation, the team hypothesizes that the UVB reflectance may be minor (similarly indicated by the ultraviolet A (UVA) radiation in **Figure 12**), and considerably less than reflection in the visible and NIR wavebands.

6.4. Mean Radiant Temperature

The on-site T_{MRT} measurements over asphalt concrete, Portland cement concrete (PCC, only in Garfield, D8), CP, and the adjacent concrete sidewalk are shown in **Table 7**. The highest T_{MRT} readings were found over CP in Garfield from 3–4pm (166.4°F), which was the hottest time of day. At that time, T_{MRT} was 164.5°F over the concrete road and 162.1°F over asphalt concrete. In Maryvale, T_{MRT} over CP was equal to T_{MRT} on sidewalks next to CP and concrete asphalt in the afternoon. Similar to T_{sfc}, minimum T_{MRT} values occurred just before sunrise, with Westcliff showing the lowest average minimum T_{MRT} (~67–69°F), which is close to T_{air} due to the absence of direct solar radiation. After sunset, T_{MRT} was 0.9 to 2.3°F cooler over CP due to reduced upwelling longwave radiation.

Table 7: Mean radiant temperature (T_{MRT}, °F) values over asphalt concrete (asphalt), concrete (for Garfield) and Cool Pavement (CP) by neighborhood, time, and location (i.e., on street (center of the road) vs. the adjacent sidewalk). Before sunrise (~4:30–5:30am), noon (12–1pm), afternoon (3–4pm), after sunset (~7:30–8:30pm).

Neighborhood	**Mean T_{MRT} ± SD (°F) Before Sunrise**		**Mean T_{MRT} ± SD (°F) Noon**		**Mean T_{MRT} ± SD (°F) Afternoon**		**Mean T_{MRT} ± SD (°F) After Sunset**	
D8 Garfield	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**
Asphalt	83.9 ± 1.0	84.7 ± 0.5	159.9 ± 2.0	156.6 ± 2.5	164.0 ± 8.4	162.1 ± 6.3	98.8 ± 1.6	99.8 ± 0.9
Concrete	83.2 ± 0.8	84.6 ± 0.0	159.1 ± 0.7	159.2 ± 0.2	163.7 ± 1.0	164.5 ± 1.1	97.1 ± 0.7	98.7 ± 0.6
CP	83.2 ± 0.8	83.7 ± 0.4	159.6 ± 3.4	164.2 ± 1.4	158.8 ± 11.7	166.4 ± 3.9	98.9 ± 1.0	98.9 ± 0.6
D5 Maryvale	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**
Asphalt	79.9 ± 1.0	80.4 ± 0.2	160.8 ± 2.7	157.5 ± 2.2	163.3 ± 5.6	160.7 ± 3.7	94.8 ± 1.8	95.0 ± 0.3
CoolSeal	79.6 ± 0.6	80.1 ± 0.2	161.7 ± 3.2	163.5 ± 2.3	163.0 ± 4.6	163.3 ± 4.9	93.1 ± 1.1	92.8 ± 0.4
D1 Westcliff	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**
Asphalt	67.7 ± 0.6	68.9 ± 0.2	152.9 ± 2.1	148.7 ± 1.6	152.7 ± 4.5	151.1 ± 2.8	81.6 ± 0.6	83.0 ± 0.4
CoolSeal	67.7 ± 1.0	67.8 ± 0.7	154.8 ± 3.8	157.9 ± 1.9	153.8 ± 3.9	154.6 ± 3.5	81.0 ± 1.6	80.8 ± 0.7

On average, T_{MRT} was elevated over CP and concrete compared to asphalt concrete during noon and afternoon hours (

Table *8*). A maximum average T_{MRT} difference between asphalt concrete and CP of 9.2°F was found in the Westcliff neighborhood at noon. T_{MRT} differences were minor before sunrise (-0.1°F to -0.7 °F) and after sunset (-0.9°F to -2.3°F) where asphalt concrete and CP performed nearly equivalent.

Table 8: Mean radiant temperature difference (ΔT_{MRT}, °F) between Cool Pavement (CP) and asphalt concrete (asphalt) or CP and concrete (in D8 Garfield) by neighborhood, time of day, and location (center of road vs. adjacent sidewalk). A negative value indicates T_{MRT} over CP is lower than over asphalt. Before sunrise (~4:30–5:30am), noon (12–1pm), afternoon (3–4pm), after sunset (~7:30–8:30pm).

Neighborhood	ΔT_{MRT} (°F) Before Sunrise		ΔT_{MRT} (°F) Noon		ΔT_{MRT} (°F) Afternoon		ΔT_{MRT} (°F) After Sunset	
D8 Garfield	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**
$T_{MRT}^{concrete} - T_{MRT}^{asphalt}$	-0.7	-0.1	-0.9	2.6	-0.4	2.4	-1.8	-1.1
$T_{MRT}^{CP} - T_{MRT}^{asphalt}$	-0.7	-1.0	-0.4	7.6	-5.2	4.2	0.1	-0.9
D5 Maryvale	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**
$T_{MRT}^{CP} - T_{MRT}^{asphalt}$	-0.3	-0.4	0.9	6.0	-0.3	2.5	-1.8	-2.3
D1 Westcliff	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**	**On Sidewalk**	**On Street**
$T_{MRT}^{CP} - T_{MRT}^{asphalt}$	-0.1	-1.0	1.9	9.2	1.1	3.5	-0.6	-2.2

6.5. Subsurface Temperatures

Overall, the CP exhibited lower T_{sub} than the control sections (**Table 9** and **Table 10**). The average difference in T_{sub} was 5.1°F for the top sensor and 4.6°F for the bottom. The quarter sections (QS)[1] with the most reduction in T_{sub} were QS 59–23 (D2) and 29–37 (D3), with a temperature difference of 10.8°F and 11.4°F, respectively. Top and bottom subsurface temperatures of CP at the Maricopa County parking lot on Madison St. were 4.2°F and 3.4°F lower than those of conventional pavements, respectively. It is important to note here that the cores with the sensors were next to each other. Limited measurements were available for Esteban Park, but results show a reduction in T_{sub} of CP by up to 1.4°F and 0.8°F, respectively. A decreased temperature gradient in the asphalt concrete is theorized to help improve pavement performance over time. The impact of these reductions in temperatures to the overall pavement performance is briefly discussed in the next section.

[1]*Note a quarter section (QS) is a tract of land that is half a mile square and contains 160 acres in the U.S. government system of land surveying.*

Table 9: Temperature difference between CP and control (asphalt concrete): Top Sensor (0.5-inch depth).

Location	Temperature Difference, °F									
	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
QS: 11-30 / District 8	-3.6	-8.3	-15.9	-	-	-	-	-	-	-
QS: 11-22 / District 4	-4.9	-7.2	-3.7	-2.5	-2.1	-1.4	**-1.7**	**-3.5**	**-3.8**	-
QS: 18-16 / District 5	-1.9	-6.7	-5.7	-4.3	-4.0	-3.6	-3.6	-4.3	-2.5	-2.0
QS: 33-18 / District 1	-0.3	-6.9	-7.0	-	-	-	-	-7.0	-7.3	-
QS: 59-23 / District 2	-	-10.1	-12.8	-9.5	-	-	-	-9.7	-12.0	-
QS: 29-37 / District 3	-	-7.0	-14.6	-12.5	-	-	-	-	-	-
QS: 26-28 / District 6	-	-	-	-4.4	-2.8	-	-	-	-2.2	-
QS: 2-19 / District 7	-	-	-	-	-	-	-	-	-0.5	-
Madison St. Parking Lot	-5.5	-4.6	-3.6	-3.6	-3.8	-3.7	-4.3	-	-	-
Esteban Park	-	-	-	-	-	-0.2	-0.9	-	-1.4	-1.4

*Note: **Bold numbers** indicate that Cool Pavement from QS 11–22 (D4) was compared to control section from QS 11–30 (D8).*

Table 10: Temperature difference between CP and control (asphalt concrete): Bottom Sensor (3-inch depth).

Location	Temperature Difference, °F									
	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
QS: 11-30 / District 8	-	-	-	-	-	-	-	-	-	-
QS: 11-22 / District 4	-5.5	-7.9	-4.7	-3.3	-2.8	-2.3	**-2.1**	**-3.4**	**-4.0**	-
QS: 18-16 / District 5	-0.2	-5.4	-4.9	-3.9	-3.4	-2.8	-2.6	-1.6	-1.8	-2.9
QS: 33-18 / District 1	-0.7	-	-	-14.3	-11.4	-3.2	-3.8	-2.6	-	-
QS: 59-23 / District 2	-	-10.2	-13.1	-10.7	-8.5	-7.6	-8.7	-7.4	-	-
QS: 29-37 / District 3	-	-6.0	-13.9	-12.1	-	-	-	-	-5.1	-
QS: 26-28 / District 6	-	-	-	-	-	-	-	-	-2.0	-
QS: 2-19 / District 7	-	-	0.4	-2.8	-3.1	-3.3	-	-	-0.1	0.9
Madison St. Parking Lot	-4.8	-4.0	-3.0	-2.6	-2.9	-3.0	-3.8	-	-	-
Esteban Park	-	-	-	-	-	-	-	-	0.0	-0.8

*Note: **Bold numbers** indicate that CP from QS 11–22 (D4) was compared to control section from QS 11–30 (D8). The underlined numbers indicate that the Cool Pavement subsurface temperature was on average higher than the asphalt concrete control for that month.*

6.6. Preliminary Performance and Lifecycle Cost Analysis

Three laboratory tests were performed on the CP coating: a thermal conductivity, heat capacity, and bonding test. The thermal conductivity test used for this analysis was developed at ASU for asphalt concrete materials. It is based on a steady-state condition of heat flow rate in the material, which is placed in a water bath where the exchange of heat occurs (**Figure 13**). The specific heat capacity is calculated based on the First Law of Thermodynamics and Heat. This law states that the total rise of energy in a system is equal to the increase in thermal energy plus the work done on the system. Finally, a Bitumen Bond Strength (BBS) test was conducted following the AASTHO TP-XX-11 standard. This method quantifies the tensile force needed to remove a pullout stub adhered to a solid substrate with asphalt concrete binders. Typically, for asphalt binders, a polished rock surface is used; however, cores from actual roadway in Phoenix (15th Ave) were used to better represent the asphalt concrete surface receiving the CP treatment.

Figure 13: a) Thermal conductivity test setup; b) Bitumen bond strength test setup.

Table 11 provides a summary for the three tests conducted on the CP. Results indicate that the CP has a higher specific heat capacity (the amount of heat required to raise the temperature of 1 gram of a substance by 1 Kelvin) than conventional asphalt concrete mixtures. Since the CP layer is very thin compared to the typical asphalt concrete layer, the higher heat capacity of the CP will have minimal impact on the temperature. The thermal conductivity results show that the CP is significantly less conductive than conventional asphalt concrete, which means that the heat will not be conducted as easily through the surface. These results are verified with the lower subsurface temperatures measured in the field. The bond strength test shows significant less bonding strength of the CoolSeal compared to conventional asphalt binders, with average strength of 34 psi compared to 230 to 276 psi. Since this test is not intended to evaluate surface treatment bond strength, the research team will be looking into implementing a revised test procedure in the future to assess bond strength and using an asphalt emulsion as a control.

To conduct a realistic pavement life cycle cost analysis, the CP performance and resulting pavement performance needs to be monitored for several years. Therefore, we used pavement performance prediction models to assess the potential for rutting and fatigue with and without the CP coating. Information about the rutting and fatigue models can be found elsewhere.[6,7] The field temperatures captured in all districts and the lower thermal gradients were used with the prediction models. The rutting and the fatigue predictions indicate that due to the lower temperatures in the pavement, the rutting and fatigue can be reduced between 3% to 13% with CP compared to pavement without CP. These are added benefits of the CP on the pavement performance itself. More testing on the durability of the CP needs to be done to determine the service life of the coating to have a better performance projection in order to carry out a life cycle cost analysis.

Table 11: Material property summary for the asphalt mixture and Cool Pavement mixture.

Material	Material Property	
	Specific Heat Capacity, J kg^{-1} °C^{-1}	Thermal Conductivity, W m^{-1}K^{-1}
Asphalt Mixture	939.68	1.001
Cool Pavement	1425.1	0.23
Material	**Bitumen Bond Strength, psi**	
	Polished Rock	**Asphalt Concrete**
Binder PG58-22	230	
Binder PG64-16	261	
Binder PG76-22	276	
Cool Seal		34

6.7. Community Survey

The community survey was launched in June 2021. Full results will be provided as an addendum to this report once a sufficient sample size has been achieved. Exploratory interviews and the pilot test survey revealed a wide range of resident perceptions regarding the CP treatment. Some residents shared strong positive impressions about the CP project, understood its intended outcomes, and expressed a desire to see the pavement applied more widely across the city. Others were skeptical about its potential positive impacts on their neighborhood and raised concerns about how it impacted their day-to-day life and impressions of their community.

Perceived cooling benefits: From both the interviews and pilot test of the survey, there was no clear consensus from residents with respect to the perceived impacts of the CP treatment on thermal comfort, with several residents indicating that they were unable to detect a change or that they needed to wait until peak summer heat to evaluate its effects. However, some residents did perceive a temperature effect shortly after installation, including one whose overall perception of the project was: *Great!"* They said that they *"could immediately tell a difference when walking the dogs. Noticed a temperature drop.*

Changed the dog walking route to accompany this." Regardless of the specific impact of the CP coating, most residents who participated in the interview or pilot survey expressed general support for additional measures to reduce urban heat.

Communication with residents: Most residents who participated in interviews and the pilot survey indicated that they had received sufficient information from the City government in advance of the CP treatment, although some expressed a desire for more participation in the process of neighborhood selection and the decision to apply the coating. Residents reported receiving a letter in the mail, door hangers, and opportunities to participate in virtual information sessions via Zoom. Respondents were generally interested to learn more about the CP process and the results from the evaluation, and several expressed an interest in participating in future meetings and workshops in their neighborhood. One resident was particularly interested in understanding more about the installation and maintenance costs of the project in comparison to other cooling strategies, including tree planting.

Visual appeal and aesthetics. Resident opinions were quite divergent with respect to the impact of the CP coating on the appearance of their neighborhood and potential subsequent impact on property values. Positive comments concerning visual appeal and aesthetics included:

"If the pavement lasts, it will bring value to the neighborhood."
"Makes the neighborhood look nicer and think that it is a point of interest for home buyers."
"People have not said much in the way of negative comments. The glaring effect is not as big of an issue."

Comments with a more negative sentiment concerning visual appeal and aesthetics included:

"It was applied in a manner that is not uniform in color."
"At first it was very glaring at had a lot of tire marks, but the glaring effect has toned down."
"I've tried to avoid the streets that have the pavement because it is blinding."
"Tire tracks and oil tend to show up more, and that looks bad over time."
"Tire marks and oil stains are obvious."

Related to the visual appearance of the CP, one resident was concerned about the City using excessive water to clean the CP streets, which they did not perceive to be a desirable tradeoff.

Surface performance and friction: Resident opinions were also divergent with respect to the experience of walking and biking on the surface. No residents in the interview and pilot survey reported significant improvements in surface performance after the CP coating was applied, but several reported no change and/or indifference. The comments with a more negative sentiment were primarily related to surface friction, although some residents raised concerns about the longevity of the coating. Sample comments related to surface performance and friction included:

"I'm nervous that it could be slick while driving and biking."
"It does not feel slippery to me personally, but my mailman said it did."
"Lifespan is not what it was expected to be, in many areas within the neighborhood it has already worn off."

Many of the comments received through the interview and pilot test suggest an opportunity for additional resident engagement and education. Some residents explicitly expressed interest in learning more about the performance of the CP coating, whereas others indicated concerns or skepticism that could be alleviated (or, potentially, exacerbated) with the data collected in the first year of the evaluation.

The City is looking forward to reviewing the complete set of feedback and perceptions obtained through the survey and will look into specific concerns raised by residents.

7. Conclusions and Recommendations for Next Steps

7.1. Conclusions

The ambitious implementation of CP by the City of Phoenix supports the real-world assessment of a novel innovation that helps address urban heat challenges and potentially related long-term sustainability issues in a hot desert city. To the project team's knowledge, this is the most extensive real-world research study of any cool pavement product, providing detailed research-grade and human-centric data collection. Indeed, numerous cities across the globe look to Phoenix for answers to heat mitigation. This one-year project allowed for a quick-response assessment during extreme heat across eight council districts, including three intensive field campaigns, to address research questions surrounding CP performance and community perception.

In summary, expected decreases in surface and sub-surface temperatures were found, which help decrease the overall urban heat load. Reductions in local air temperature were small, and the increased reflectivity led to higher mean radiant temperature on the streets, decreasing thermal comfort. This may be a necessary tradeoff to reduce surface temperatures. Importantly, all temperature differences measured between the CP and asphalt concrete portions of the neighborhoods varied by time of day and neighborhood.

The reductions in the surface and sub-surface temperature are positives for improving the lifespan and performance of the pavement; however, longer-term testing is necessary for assessing the changes in solar reflectivity, traction, and degradation.

Preliminary results from resident interviews and surveys reveal satisfaction with communication from the City about the CP pilot program and interest in learning more from the evaluation. Residents' opinions diverged regarding visual appeal and aesthetics, impacts on property values, the longevity of the coating, and surface friction. Collectively, the interview and preliminary survey results point to opportunities for additional resident engagement and education concerning CP.

Overall, the holistic assessment of numerous physical and social indicators of the CP at various timescales provides critical insight for future work, as well as useful information for the City of Phoenix and cities globally with similar goals. Recommendations and next steps are outlined below.

7.2. Recommendations & Next Steps

Often, cities of the Southwest, and specifically Phoenix, are looked to as testbeds for urban resilience to the stresses of water resources, extreme heat, and population growth.[8] Critical assessments of interventions attempting to reduce these impacts are paramount to determine the value of more widespread implementation. The CP Pilot Program, and assessments beyond the initial pilot program, are vital to further the City's urban resilience.

Based on Year 1 data collection and results of the pilot project throughout the City of Phoenix, the following recommendations and next steps were discussed in a joint workshop between key City of Phoenix and ASU personnel. In particular, the group is interested in gaining more conclusive results regarding key indicators, such as the optimal use and placement of CP and/or similar products, the long-term durability and life cycle assessments, and performance regarding specific climatic conditions. The group agreed that for many of these indicators, conclusive evidence cannot be determined after only one year, particularly issues related to durability and life cycle assessment. In the recommended follow-up study, we propose to include more side-by-side applications using some of the most promising products in the industry and expanded laboratory testing to better understand their abrasion resistance generated by traffic and/or climatic effects. As part of all recommendations listed below, continued and expanded engagement with residents and communities will be important. The next step recommendations are:

1. Create a research test bed on local streets comparing various types of CP products of differing formulations, including a gray coating ("special black") created by GuardTop® that may hide issues of dirt and degradation by vehicles for resident satisfaction. As part of this, the team proposes discussions with the City staff about the possibility of including other promising products in this area. These test beds will allow for more controlled experimentation, and the further exploration of other pavement coatings with similar performance yet darker colors may help improve aesthetics and public perception.

2. Calculate societal/environmental impacts related to the potential reductions in energy and water use due to T_{sfc} and T_{air}. Energy and water use are primary concerns during hot Phoenix summers due to droughts, electric grid strain, and population growth. Thus, potential energy and water savings are critical to quantify across various heat mitigation types,[9,10] and may also help the public understand the value of the CP technologies.

3. Perform more controlled, simultaneous, long-term tests of fine-scale T_{air} variations by height (vertical gradient) using highly accurate thermocouples while controlling for any potential localized effects of residential neighborhood design. As part of this, there may be added value in completing these T_{air} experiments in a testbed (#1 above) comparing different types of CP, as well as a new darker seal. This experiment will help tease apart local microclimatic design impacts and the influence of air mixing on T_{air} differences between traditional asphalt concrete and CP, thus providing more accurate T_{air} results for use in #2 above.

4. Evaluate how the pavement condition (before the application) plays an important role in the long-term bond strength and durability. The recommended follow-up study could develop guidelines regarding pavement condition, timing, and location.

5. Assess interactions of CP and trees shade to determine if treed streets (such as new cool corridors) are sensible locations for effective use of CoolSeal by GuardTop® or other CP products versus more open streets and parking lots. Given that numerous heat mitigation efforts can work in concert to reduce urban air and surface temperatures and provide shading for comfort, it is important to assess separate and interactive effects of trees and CP locations to provide the most appropriate recommendations for the goals of a given location/neighborhood.

8. References

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Appendix 1: Survey Questions

Phoenix Cool Pavement Survey, Spring 2021

Start of Block: Consent

Q0
Thank you for your time today. Our team is conducting a survey to gain a better understanding of the public's opinion and perception about the newly applied pavement coating in your neighborhood. We are affiliated with the Urban Climate Research Center at Arizona State University.
We are inviting your participation in a short survey that we estimate will take **no more than 10 minutes** to complete. You have the right not to answer any question, and to stop participation at any time.
Your participation in this study is voluntary. If you choose not to participate or to withdraw from the survey at any time, there will be no penalty, but your option to acquire the $5 gift card for completing the survey will be discarded. **You must be 18 years or older and have an address that resides within a neighborhood with the new pavement coating to be a valid participant.**
The direct benefits that you can expect to receive after partaking in this survey are the ability to voice your opinion regarding a public feature that was implemented by your local government, and a $5 gift card. The results that we receive will be used to conduct further data analysis and interpretation for our project and will be shared with city staff and other researchers. There are no foreseeable risks or discomforts to your participation.
The data we collect in this survey will be anonymous. Your anonymity will be maintained by never using your name or other personally identifying information alongside your responses. If you have any questions concerning the research study, please contact the research team director, David Hondula, at 480-965-4794 or david.hondula@asu.edu. If you have any questions about your rights as a subject/participant in this research, or if you feel you have been placed at risk, you can contact the Chair of the Human Subjects Institutional Review Board, through the ASU Office of Research Integrity and Assurance, at (480) 965-6788.

Urban Climate Research Center
Arizona State University

Q79 Do you agree to participate in this study?

◯ Yes (1)

◯ No (2)

End of Block: Consent

Start of Block: Code

Q81 Please input the six-digit code located on the postcard you received in the mail that invited you to complete this survey. The code begins with PT and four numbers following it (e.g., "PT9876").

____

End of Block: Code

Start of Block: Screening Questions

SCInfo
Thank you for taking this survey. Our first few questions confirm your eligibility to take this survey.

Please remember that you can skip any questions that you prefer not to answer.

SC1 Have you lived at this address since at least the summer of 2020?

◯ Yes (1)

◯ No (2)

Q78 Periodically, the city resurfaces neighborhood streets to increase its longevity. Was a lighter-colored (white or gray) coating applied to the street in front of your home in 2020?

A sample picture of the coating is on the postcard that you received that invited you to participate in this survey.

- ◯ Yes (1)
- ◯ No (2)

End of Block: Screening Questions

Start of Block: Impressions of Pavement

HHInfo **We'd next like to learn about your impressions of the lighter-colored pavement coating that was applied to your street last year in place of the regular dark-colored coating. On the rest of the survey, any use of terms like "coating" or "treatment" refers to the lighter-colored (white or gray) coating applied to your street last year.**

HH1 How did you learn that your street was going to receive the coating? Please check all that apply.

- ◯ From someone I know (1)
- ◯ From an announcement on traditional media like television, newspaper, or radio (2)
- ◯ From an announcement on social media or the internet (3)
- ◯ From a flyer or pamphlet left at my home (4)
- ◯ Online public engagement by city (a public meeting held virtually) (5)
- ◯ I did not learn that my street was to receive the coating until it happened (6)
- ◯ Other (7)

Q99 If you received a flyer or pamphlet from the city informing you that your street was to be treated, was it in the language you primarily speak at home?

- ○ Yes (1)
- ○ No (2)
- ○ Other (3) ____

HH5 Before it was applied, what did you understand the primary purpose(s) of the lighter-colored coating to be?

____

____

____

____

____

HH6 What is your overall level of satisfaction with the lighter-colored coating?

- ○ Very dissatisfied (1)
- ○ Dissatisfied (2)
- ○ Neither satisfied or dissatisfied (3)
- ○ Satisfied (4)
- ○ Very Satisfied (5)

HH7 What are the main reason(s) that you selected your answer for the previous question?

____

____

____

____

____

End of Block: Impressions of Pavement

Start of Block: Specifics

ELInfo **Thanks for your responses thus far. We now have a few more specific questions related to the lighter-colored pavement coating that was applied to your street.** We would like to know if you think the lighter-colored coating has any impact on the temperature of your neighborhood and if it has impacted how comfortably cool or warm you might be as you walk on your neighborhood streets. Please select the best response for each of the questions below.

El1 During the mornings and evenings, the coating makes my neighborhood…

- ○ Cooler (4)
- ○ Warmer (5)
- ○ No change (6)
- ○ Not sure (7)

EL2 During the middle of the day, the coating makes my neighborhood…

○ Cooler (1)

○ Warmer (2)

○ No change (3)

○ Not sure (5)

EL3 At night, the coating makes my neighborhood…

○ Cooler (1)

○ Warmer (2)

○ No change (3)

○ Not sure (4)

EL4 We would now like to learn about some other possible impacts of the lighter-colored coating on you, your home, and your neighborhood.

Please select the best response for each of the questions below.

Q83 The coating makes my neighborhood look…

- Better (1)
- Worse (2)
- No change (3)
- Not sure (4)

Q84 The coating has made property values in my neighborhood…

- Rise (1)
- Fall (2)
- No change (3)
- Not sure (4)

Q85 When it comes to walking and biking in my neighborhood, I try to use streets with the coating…

- More often (1)
- Less often (2)
- No change (3)
- Not sure (4)

Q86 When it comes to my pets walking on the coated streets, they seem to:

- Prefer them (1)
- Avoid them (2)
- No change (3)
- Not sure (4)
- Don't have pets (9)

Q87 The coating has made my streets…

- Have more glare (1)
- Have less glare (2)
- No change (3)
- Not sure (4)

Q88 The coating has made my streets…

- More slippery (1)
- Less slippery (2)
- No change (3)
- Not sure (4)

Q89 Phoenix should…

- ○ Apply the coating to more streets in my neighborhood (1)
- ○ Get rid of the new coating on the streets in my neighborhood (2)
- ○ Leave things as they are now (3)
- ○ Not sure (4)

End of Block: Specifics

Start of Block: Demographics

CIInfo
We're nearly at the end! To understand who took the survey, we would like to learn a little bit more about you and your neighborhood.

---

*

CI1 What is your age in years?

____

CI7 Is anyone who lives in your household 18 years of age or younger?

- ○ Yes (1)
- ○ No (2)

Q90 Is anyone who lives in your household 65 years of age or older?

- ◯ Yes (1)
- ◯ No (2)

DE4 What do you consider your gender?

- ◯ Female (1)
- ◯ Male (2)
- ◯ Other (3) ____
- ◯ Don't know (5)

DE3 With which group or groups do you identify? Choose all that apply.

- ☐ Native American or American Indian (1)
- ☐ Asian or Asian American (2)
- ☐ Black or African American (3)
- ☐ Hispanic, Latino, Mexican, Mexican-American or Spanish (4)
- ☐ Middle Eastern (5)
- ☐ Native Hawaiian or Other Pacific Islander (6)
- ☐ White (7)
- ☐ Other (8) ____
- ☐ Don't know (9)

Q93 Do you have access to a personal vehicle that you can use regularly?

- ○ Yes (1)
- ○ No (2)

Q92 Is walking or biking part of your primary mode of transportation to get to work, school, or other obligations?

- Yes (1)
- No (2)

Q91 How many days each week do you walk or bike in your neighborhood?

- 0 (1)
- 1 (13)
- 2 (14)
- 3 (15)
- 4 (16)
- 5 (17)
- 6 (18)
- 7 (19)

Q96 How serious do you think the health risks of summer heat are to you and the people who live in your household?

- ◯ Very serious (1)
- ◯ Somewhat serious (2)
- ◯ Not too serious (4)
- ◯ Not at all serious (5)
- ◯ Don't know not sure (6)

Q95 How many years have you lived in the Phoenix area?

____

Q97 How would you rate the overall quality of life in the City of Phoenix today?

- ◯ Extremely good (23)
- ◯ Somewhat good (24)
- ◯ Neither good nor bad (25)
- ◯ Somewhat bad (26)
- ◯ Extremely bad (27)

Q98 Thinking about last year’s summer, to what extent do you think your neighborhood was cooler or hotter than other neighborhoods in the City of Phoenix?

○ A lot cooler (1)

○ A little cooler (2)

○ About the same temperature as other neighborhoods (3)

○ A little hotter (4)

○ A lot hotter (5)

○ Don't know/unsure (6)

End of Block: Demographics

Start of Block: Follow ups

DEInfo **We have a few final questions about follow-up activities.**

Arizona State University is partnering with the City of Phoenix to study the performance of the pavement coating.

DE5 Would you like to receive results from our pilot study about the newly coated pavement as they become available?

○ Yes (1)

○ No (2)

Q100 Would you be willing to participate in a future interview, group discussion, or other activity to help researchers and the city more clearly understand your opinions?

◯ Yes (1)

◯ No (2)

Q101 Would you like to participate in any educational programs or public events related to the pavement coating that was applied in your neighborhood?

◯ Yes (1)

◯ No (2)

Q102 How can we contact you for the follow-up activities you said you might be able to participate in? *You do not need to enter any information if you do not wish to be contacted. We will store your contact information separately from your responses.*

◯ Phone (3) ____

◯ Email (1) ____

◯ No further participation (7)

Q104 If you would like to receive a $5 gift card for your participation, please provide us with your preferred mailing or email address.
You do not need to enter any information if you do not wish to be contacted. We will

store your contact information separately from your responses.

- ◯ Mailing address (3) ____
- ◯ Email (1) ____
- ◯ Prefer not to receive gift card (7)

DE18 Is there anything else that you would like to share with us about the pavement coating that was applied in your neighborhood?

____

____

____

____

____

End of Block: Follow ups

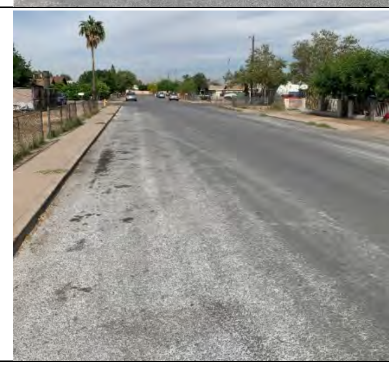
Start of Block: EndText

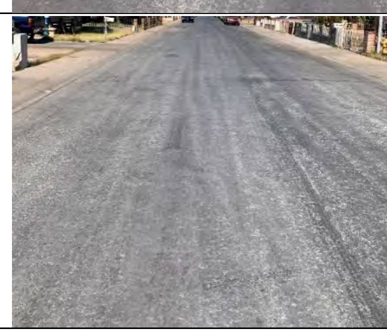
Q48 Thank you very much for taking the time to participate in this survey. If you opted to receive a gift card, we will distribute to you it within the next few weeks.

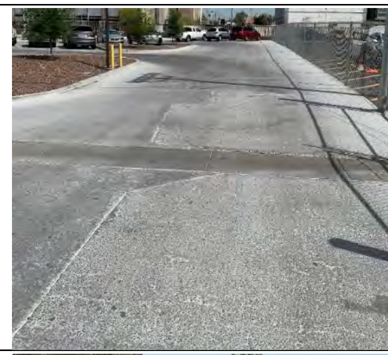
If you have any questions or concerns about the survey, please e-mail or call David Hondula at Arizona State University: david.hondula@asu.edu, 480-965-4794.

End of Block: EndText

Appendix 2: Current Pavement and CoolSeal Conditions

Location	Condition	Photo
QS: 11-30	• Pavement is in good condition. • Few low severity cracks starting to form block cracking. • CoolSeal in good condition with no signs or coating wear. Some discoloration/tracking in the wheel path are observed	
QS: 11-22	• Pavement is in good condition. • Few low severity cracks observed • CoolSeal in good condition and has not wear away. There a few locations showing discoloration/tracking in the wheel path. • Some oil stains observed in the parking areas.	
QS: 18-16	• Pavement is in fair condition. • Considerable amount of block cracking of low to moderate severity throughout the quarter section. Some alligator cracking. • CoolSeal in good condition with no signs of wear. Some discoloration in the wheel path. • Some oil stains observed	
QS: 33-18	• Pavement in good condition. • Some roads with longitudinal cracking (construction joint) and some transverse cracking. • CoolSeal coating is still in good condition, however, some discoloration/tracking is observed in the wheel path.	

Location	Condition	Photo
QS: 59-23	• Pavement in good condition with some block cracking. • The cracks are shown and some of them open. The crack severity is low. • CoolSeal is in good condition and has no wear away. Minor discoloration/tracking is observed in the wheel path.	
QS: 29-37	• Pavement in overall good condition. • Some longitudinal cracking. • CoolSeal shows some discoloration/tracking across the width of the pavement, but the coating is still visible.	
QS: 26-28	• Pavement in overall good condition. • Very few low severity crackings. • CoolSeal is in good condition at the edges but showing some tracking in the wheel path.	
QS: 2-19	• Pavement in overall good condition. • No distresses observed. • CoolSeal in good condition but dirty showing some tracking in the wheel path.	

Location	Condition	Photo
Madison St. Parking Lot	• Pavement in overall good condition. • No distresses observed. • CoolSeal is in good condition but the difference in color is evident in the wheel path compared to the edges.	
Esteban Park	• Pavement in overall good condition. • The crack seal previously applied can be observed through the CoolSeal coating. • CoolSeal is in good condition with some discoloration/tracking in the wheel path.	

Appendix 3: Surface temperature maps

Figure A1. Map of measured and time-detrended surface temperature for 4:50 AM on August 18, 2020, in the Garfield neighborhood in district 8.

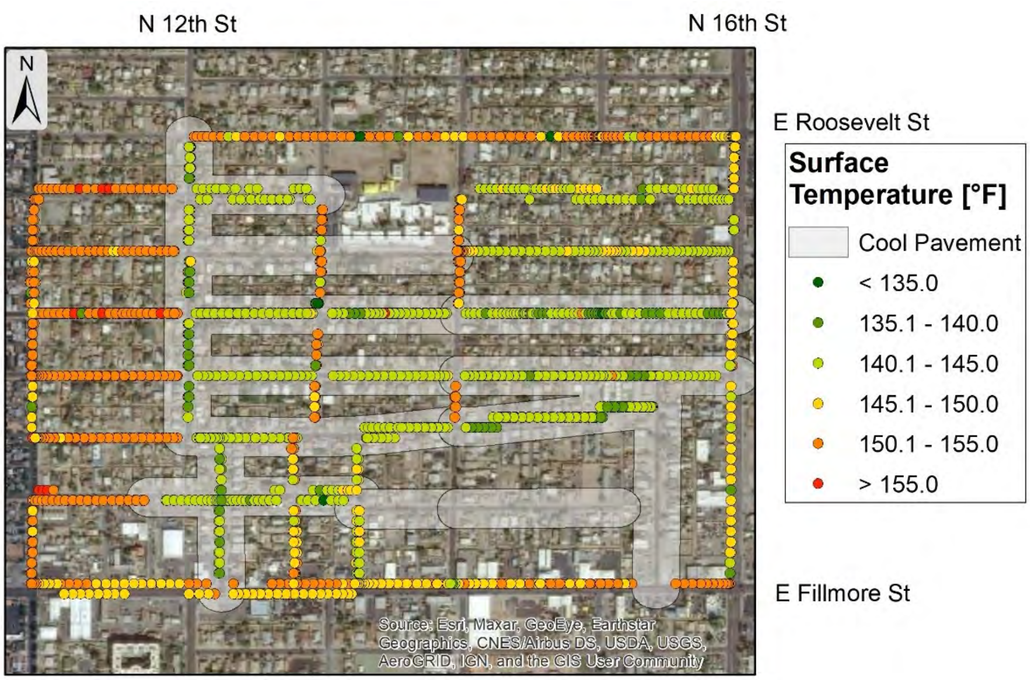


Figure A2. Map of measured and time-detrended surface temperature for 3:30 PM on August 18, 2020, in the Garfield neighborhood in district 8.

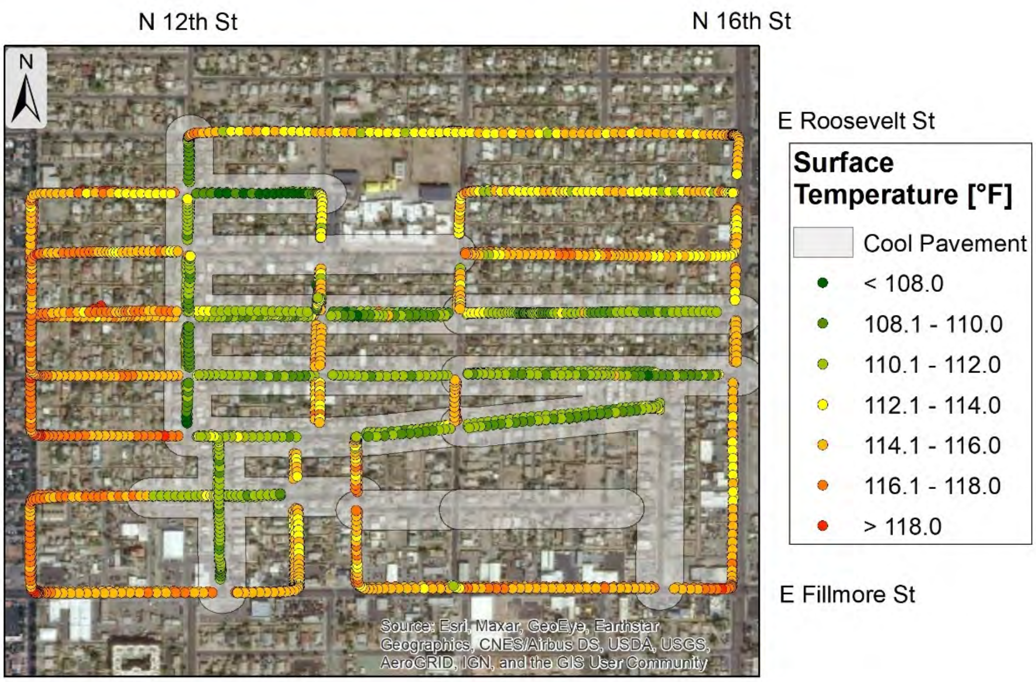


Figure A3. Map of measured and time-detrended surface temperature for 8:20 PM on August 18, 2020, in the Garfield neighborhood in district 8.

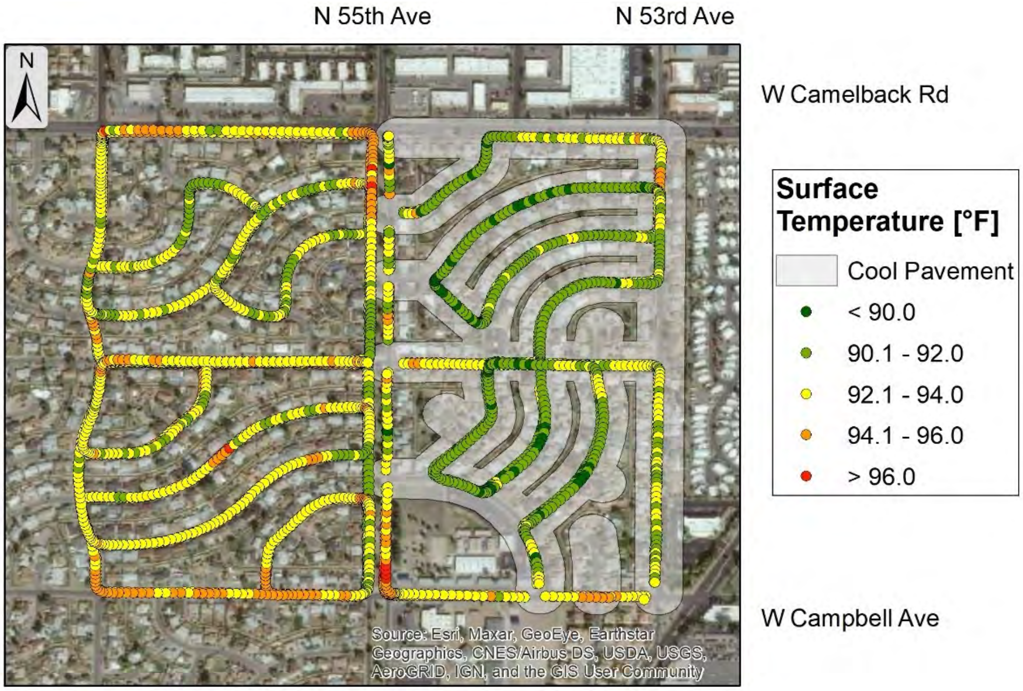


Figure A4. Map of measured and time-detrended surface temperature for 5:20 AM on September 5, 2020, in the Maryvale neighborhood in district 5.

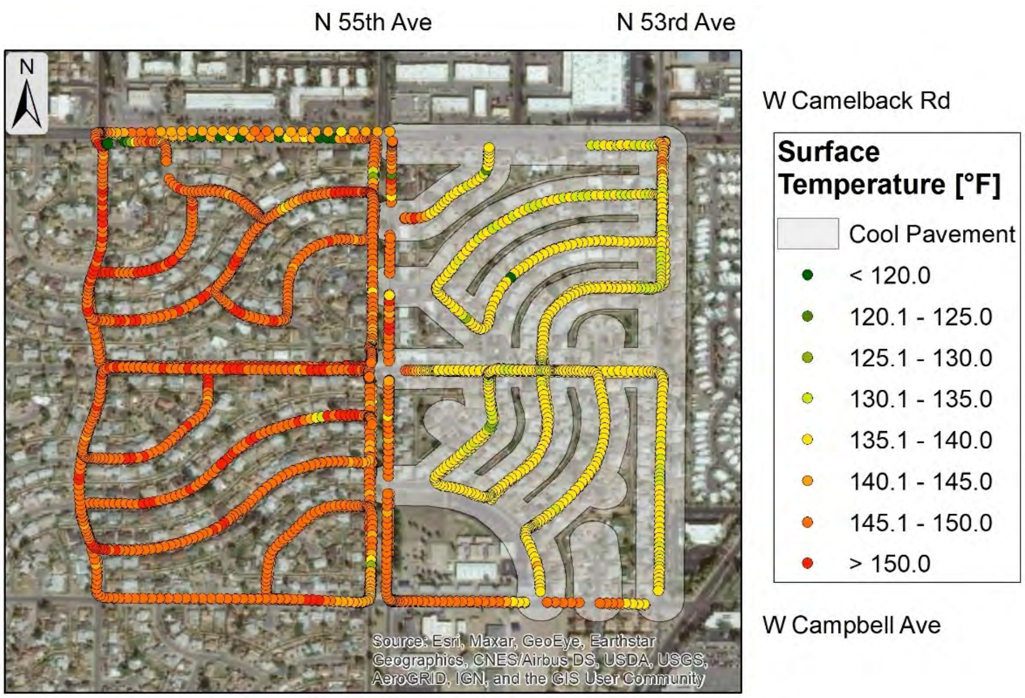


Figure A5. Map of measured and time-detrended surface temperature for 12:30 PM on September 5, 2020, in the Maryvale neighborhood in district 5.

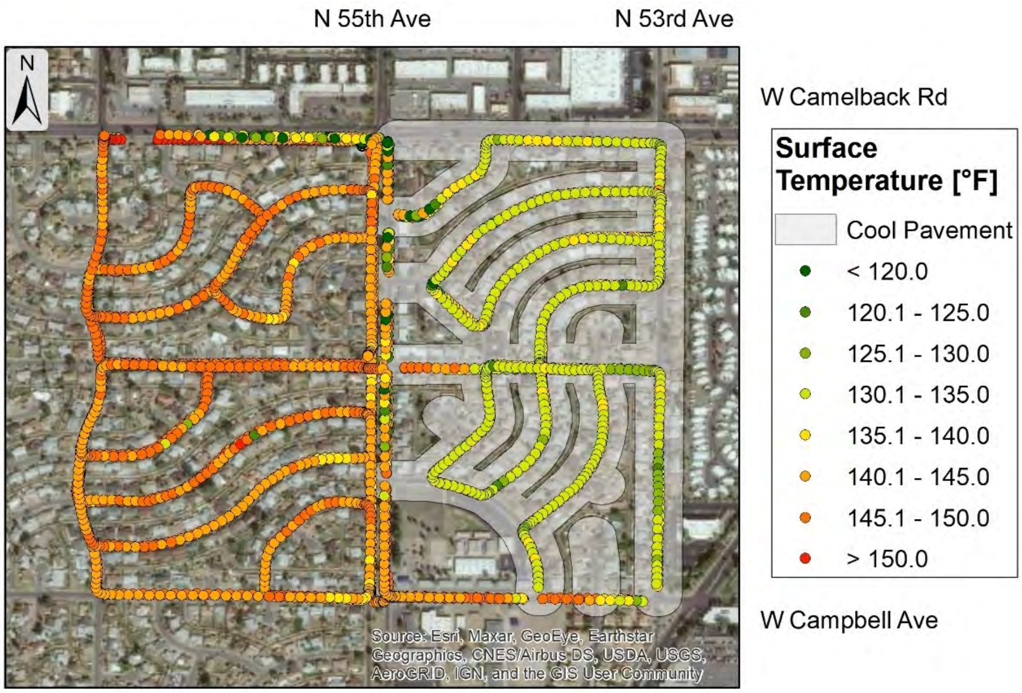


Figure A6. Map of measured and time-detrended surface temperature for 3:30 PM on September 5, 2020, in the Maryvale neighborhood in district 5.

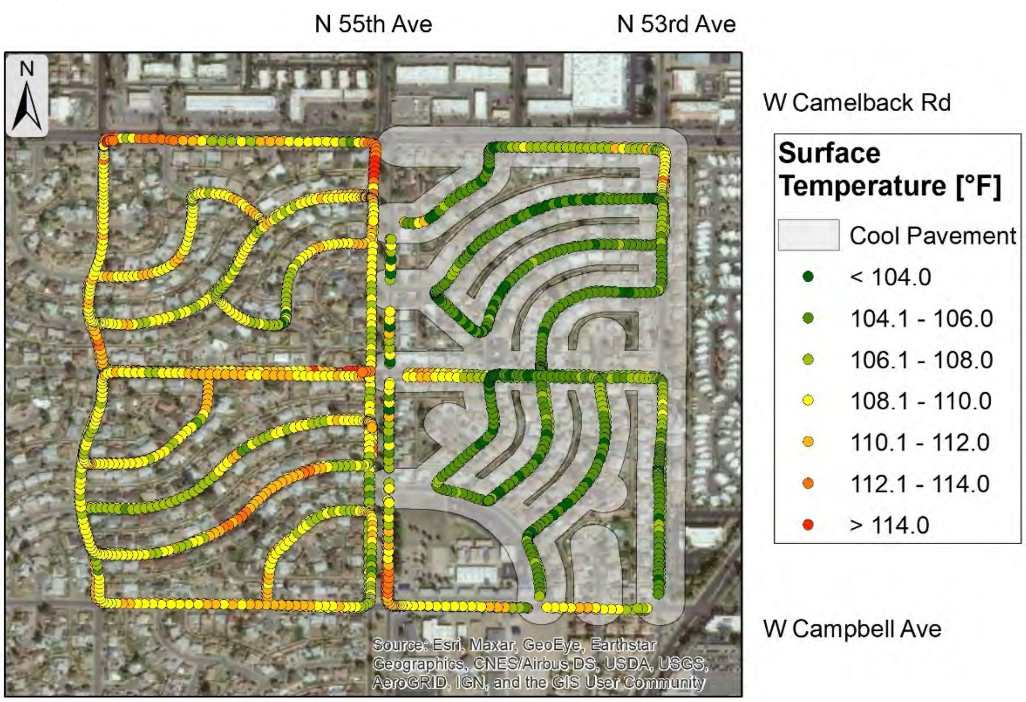


Figure A7. Map of measured and time-detrended surface temperature for 8:00 PM on September 5, 2020, in the Maryvale neighborhood in district 5.

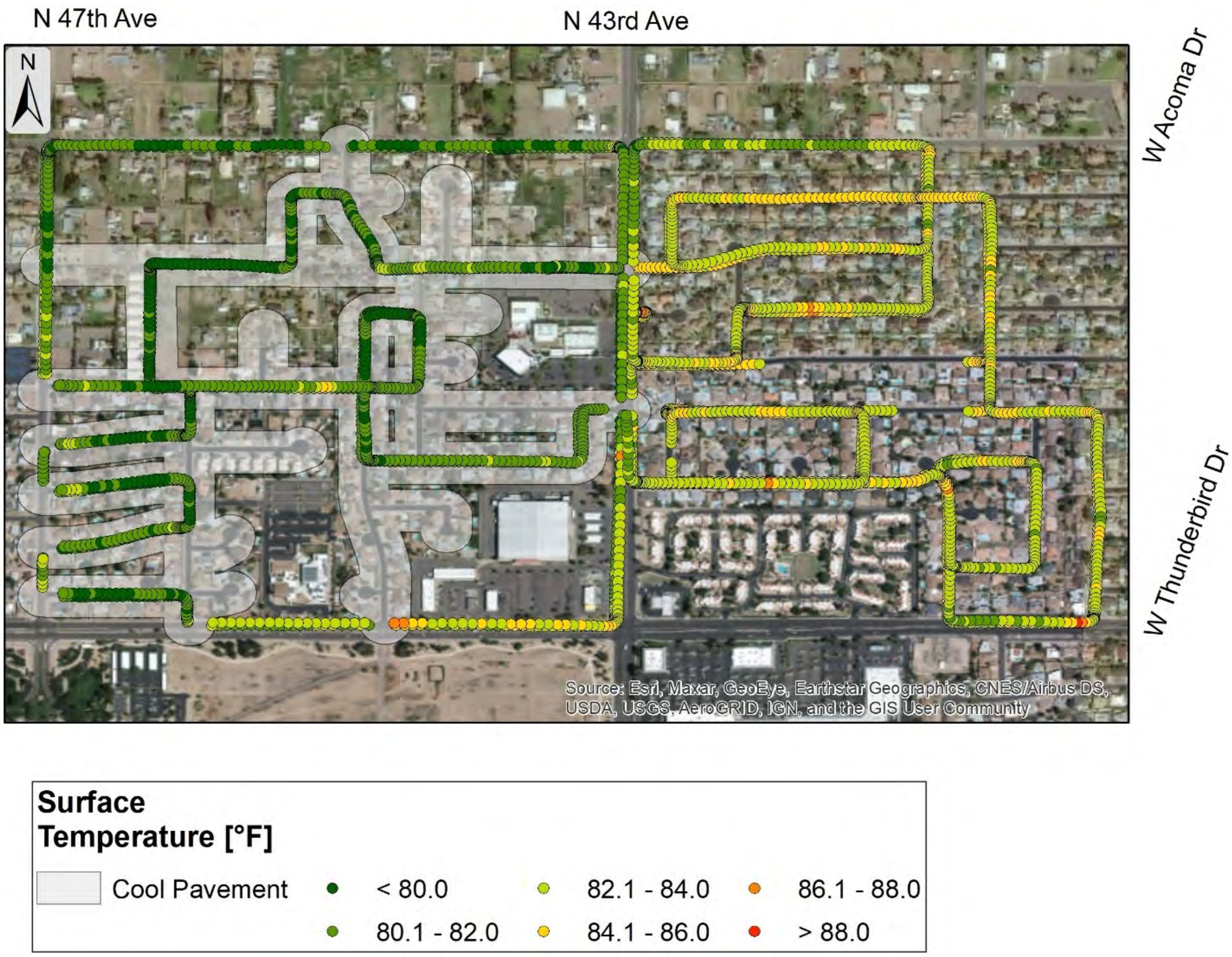


Figure A8. Map of measured and time-detrended surface temperature for 5:20 AM on September 20, 2020, in the Westcliff neighborhood in district 1.

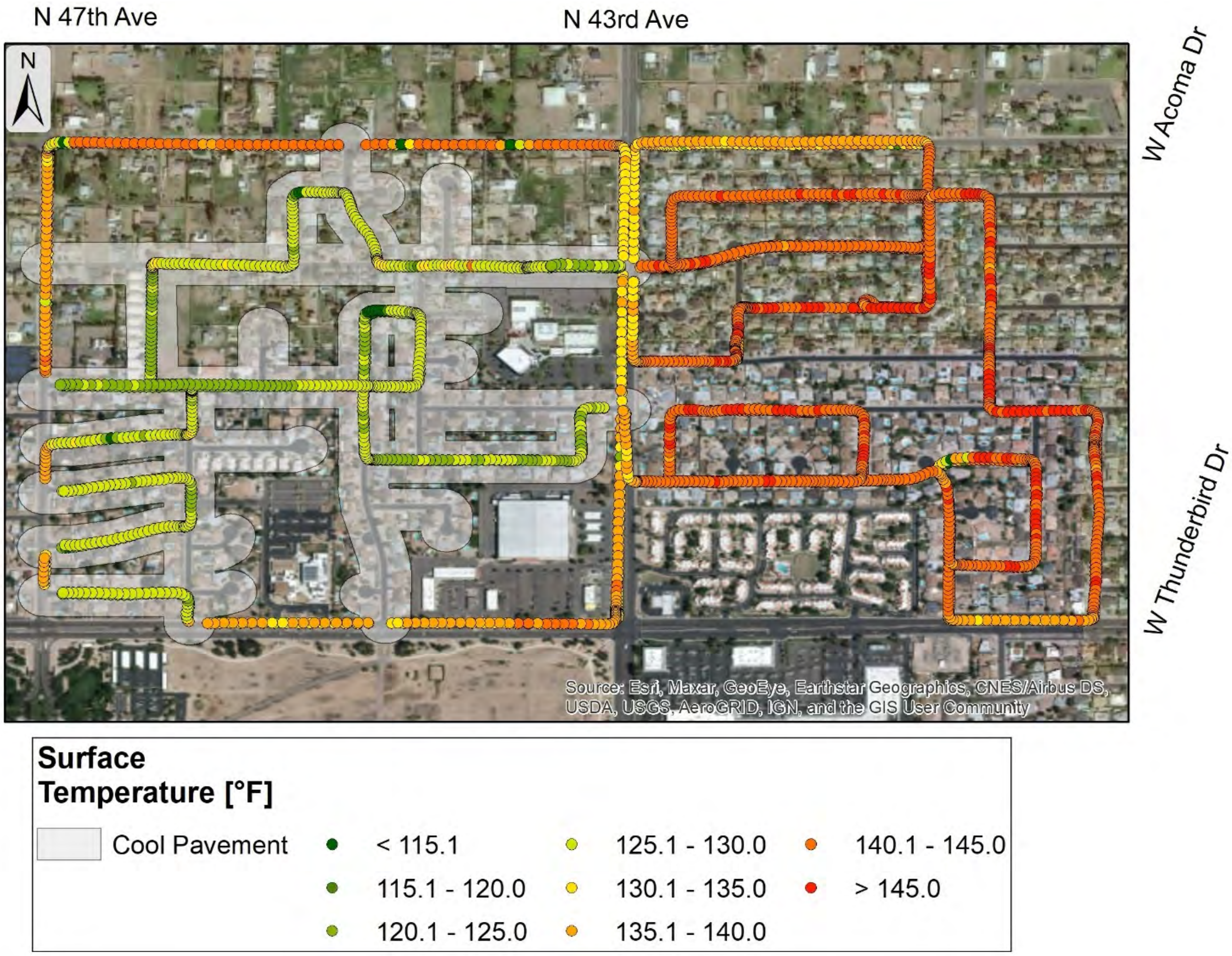


Figure A9. Map of measured and time-detrended surface temperature for 12:30 PM on September 20, 2020, in the Westcliff neighborhood in district 1.

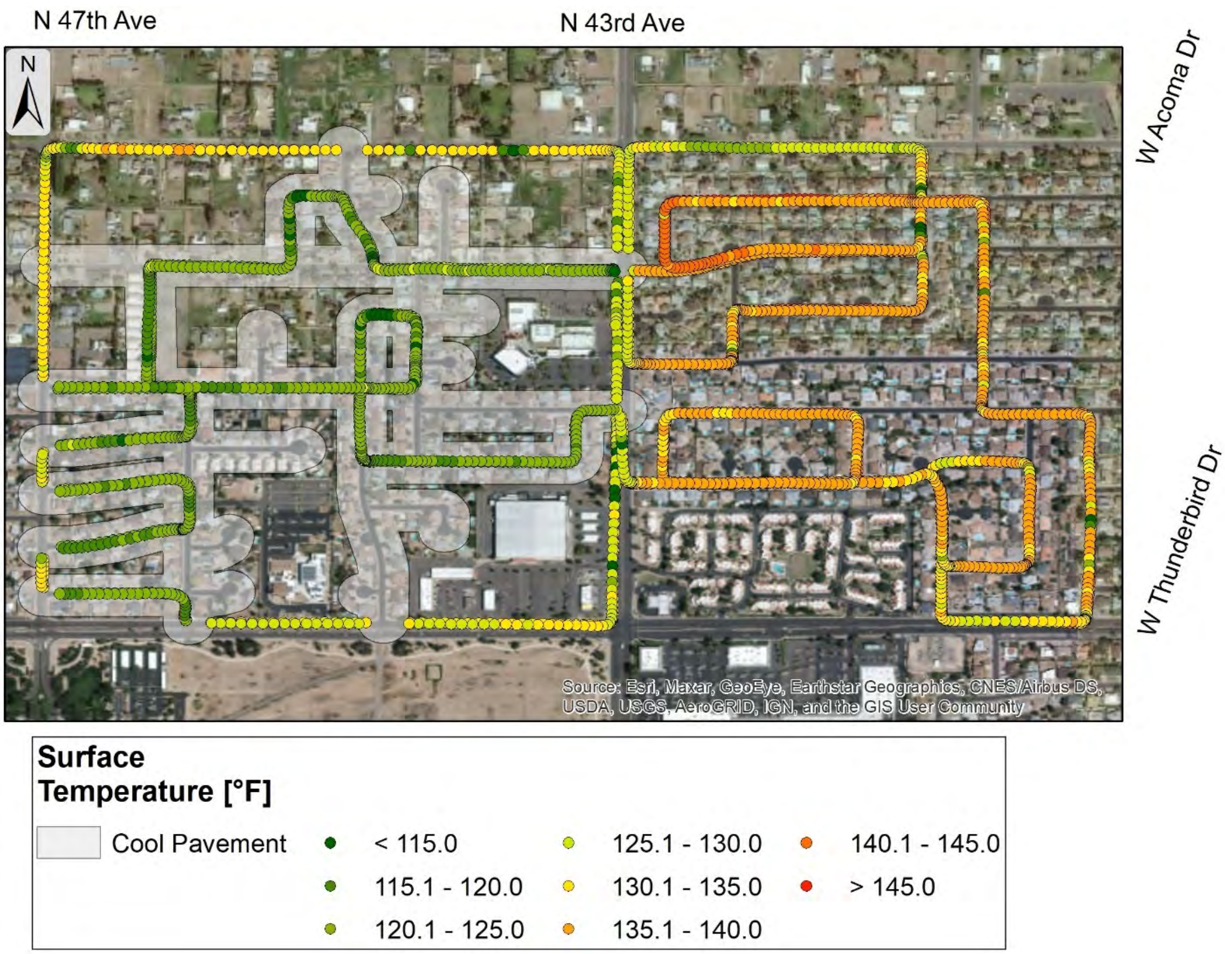


Figure A10. Map of measured and time-detrended surface temperature for 3:30 PM on September 20, 2020, in the Westcliff neighborhood in district 1.

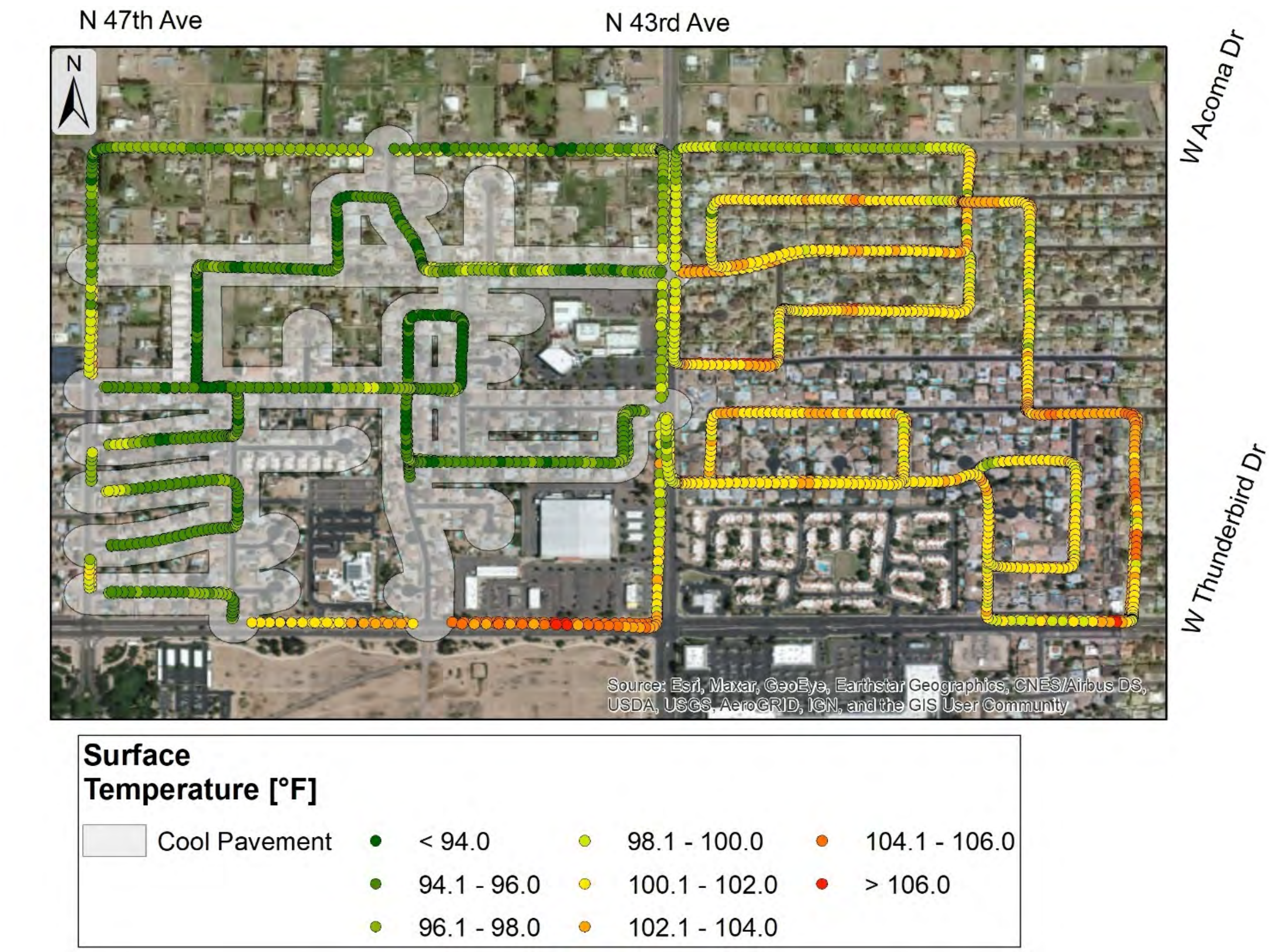


Figure A11. Map of measured and time-detrended surface temperature for 7:40 PM on September 20, 2020, in the Westcliff neighborhood in district 1.

Appendix 4: Sensor specifications

	Sensor	Variable(s)	Range	Accuracy	Sensor Time Constant/Response Time	Height
A	EE181 (Pt1000 Class A, HC101)	Air Temperature	-40–60°C	±0.2°C	[63% step change (1 m s^{-1} air flow at sensor)] ≤22 s	1.5 m
		Relative Humidity	0–100%	-15–40°C: ≤90% RH ± (1.3 + 0.003 • RH reading) % RH -15–40°C: >90% RH ± 2.3% RH -25–60°C: ± (1.4 + 0.01 • RH reading) % RH -40–60°C: ± (1.5 + 0.015 • RH reading) % RH	[63% of a 35 to 80% RH step change (1 m s^{-1} air flow at sensor)] ≤22 s	1.5 m
B	Gill 2D WindSonic	Wind Speed	0–60 m s^{-1} (116 knots)	±2% @12 m s^{-1}	0.25 seconds	1.7 m
		Wind Direction	0–360°	±2° @12 m s^{-1}		
C	GPS16X Garmin GPS	Latitude/ Longitude	Temperature: -30–80 °C operational	Position: Less than 15 m, 95% typical (100 m with selective availability on)	1 s (all data known)	1.5 m
				Velocity: 0.1 knot RMS steady state		
D	3 NR01 Hukseflux 4-Component Net Radiometers (oriented up/down, left/right, front/back)	Shortwave Radiation	–2000 W m^{-2}; spectral range 305–2800 nm (50% transmission points)	± 10% for 12-hour totals, day and night	[for 95% response] 18 s	1.1–1.3 m
		Longwave Radiation	–1000 W m^{-2}; spectral range 4500–50000 nm (50% transmission points)			
E	Fine-wire thermocouple	Air Temperature	N/A	±0.5°C to ±1.0°C	1 s	2.0 m
F	Apogee SI-111 Infrared Radiometer	Surface Temperature	8 to 14 µm (corresponds to atmospheric window)	±0.5°C (-40° to +70°C)	< 1 s (to changes in target temperature)	30 cm